Technical Options for the Advanced Liquid Metal Reactor

May 1994

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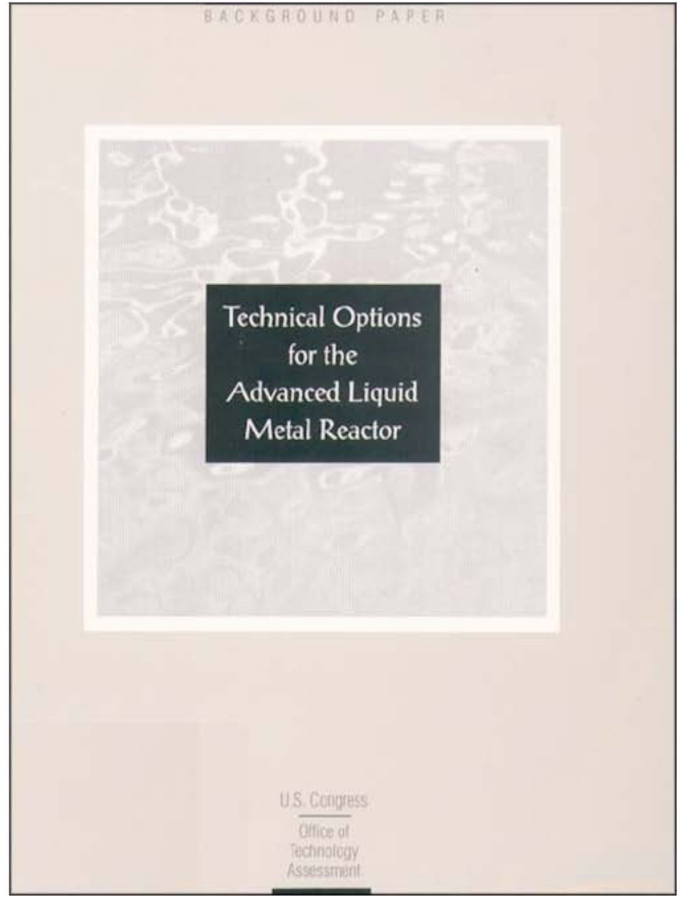

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Foreword

In this post-Cold War era, scientists and engineers have focused much research on the development of technologies to address the legacy of the nuclear arms race. One of the more intractable problems currently is how to dispose of excess plutonium from retired nuclear weapons and how to manage radioactive plutonium waste. The Office of Technology Assessment covered this issue in its 1993 assessment *Dismantling the Bomb and Managing the Nuclear Materials.* The House Committee on Energy and Commerce, Subcommittee on Energy and Power, asked OTA to expand the technical analysis of the advanced liquid metal reactor (ALMR).

This background paper discusses the history and status of the ALMR research program. It presents applications of this technology to the plutonium disposition problem and the possible advantages and disadvantages of its future development and deployment. It also discusses related issues such as waste management and concerns about proliferation of plutonium material.

With regard to its application to the plutonium disposition problem, ALMR technology will require a decade or more of research and testing before the performance of a complete system could be ensured. Even though complete elimination of the plutonium isotope within the reactor is theoretically achievable with this technology, other aspects of full-scale deployment must be considered in setting goals and objectives for a development program.

OTA appreciates the assistance and support it received for this effort from many contributors and reviewers, including the Argonne National Laboratory, the General Electric Company, the Department of Energy, other independent research organizations and public interest groups, and many individuals. They provided OTA with valuable information critical to the completion of this paper and important insights about its technical evaluations and projections. OTA, however, remains solely responsible for the contents of this report.

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Note: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the reviewers. The reviewers do not. however, necessarily approve, disapprove, or endorse this background paper. OTA assumes full responsibility for the background paper and the accuracy of its contents.

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Introduction and Summary 1

In September 1993, the Office of Technology Assessment (OTA) published *Dismantling the Bomb and Managing the Nuclear Materials, a* report on the technical and policy issues involved in dismantling nuclear warheads in the United States and Russia as well as the long-term care of the materials extracted from these warheads. OTA concluded, and several other recent reports have confirmed *(48,* 27, 37), that disposing of plutonium from warheads is one of the more intractable problems that remain as a legacy of the Cold War nuclear arms race. In addition, the OTA report stressed the need to formulate national policy goals on plutonium control and disposition prior to adopting major technical paths.[1]

Although few readily available methods, other than long-term storage, currently exist for plutonium disposal, many proposals have been put forward to develop. adapt, or apply new advanced technologies for this purpose. One such technology that has been proposed is the so-called advanced liquid metal reactor/integral fast reactor (ALMR/IFR, or ALMR system). OTA reviewed the merits of this system briefly in its dismantlement report. The Department of Energy (DOE) has been supporting a research program to develop this system for many years. Basic research on liquid metal reactor systems began more than four decades ago. The work supported by DOE's Office of Nuclear Energy in the 1970s and 1980s was part of a major effort to develop breeder reactors that would produce plutonium and power at the same time. More

[1] In fact, in early 1994, the Department of Energy established a department-wide initiative for control and disposition of surplus fissile materials as well as a new office to plan and implement a long-range strategy.

recently, the developers of this technology have claimed that essentially the same concept could be used to consume plutonium and meet such goals as disposing of surplus plutonium from nuclear warheads.

This paper evaluates the ALMR program, its current status and potential for plutonium disposal, and certain key questions that have been raised about what benefits or risks this technology may offer if it is fully developed and deployed in the future. The program itself has a long and complicated history. The technology for plutonium disposal would include a nuclear reactor, a fuel manufacturing and reprocessing system, and many ancillary components. Some of these components are already developed, while others are in the early testing phase or have not yet been designed. In general, the overall technology is still in the research stage, and many claims about its potential are based on assumptions about the successful outcome of future development and testing work.

Since the ALMR system has been promoted for a variety of purposes, the features and subsystems of the total project have necessarily changed to fit each purpose. Therefore, any analysis of the advantages or disadvantages of this technology should be made separately for each purpose proposed. OTA has attempted to conduct this evaluation in such a way as to limit its analyses primarily to the newly proposed objectives, without making judgments about the future of nuclear power in general.

During FY 1992 and 1993, DOE supported the ALMR research program at a level of approximately $40 million to $43 million annually. These funds were allocated to the Argonne National Laboratory, which received almost 80 percent of the budget, and to the General Electric Company (GE), which received about 20 percent. Argonne has conducted this work at its laboratory and research offices in Chicago, as well as at its test facility known as "Argonne West," which is located in the Idaho National Energy Laboratory. Recently, Argonne's work focused on the development of the reactor fuel reprocessing portion of the total system, which is one of the important and necessary components for the plutonium disposal application. GE efforts, however, have focused on a total commercial power generating system that is not closely related to the key development needs for plutonium disposition applications.

In 1993, Congress debated whether continued funding for this program could be justified. Issues were raised about the most appropriate goals for the program and whether there was sufficient justification for funding the program at various levels. The final FY 1994 appropriation for the program was about $30 million. In the President's FY 1995 budget as submitted to Congress in January 1994, the Administration proposed to cut almost $100 million from Nuclear Energy research and development (R&D) programs in general and to terminate the ALMR project.

FOCUS OF OTA'S ANALYSIS

This paper, which presents OTA's evaluation of the ALMR project, first reviews the history of government programs and recent program goals for developing 1 liquid metal fast reactors, and then focuses on four key questions that have been posed about the technology's potential for specific purposes:

1. What is the potential for this technology in disposing of surplus weapons plutonium?
2. What is its potential for processing spent fuel from light-water reactors and for destroying plutonium and other actinides?
3. What is its potential for processing other radioactive wastes that are currently stored under marginal conditions?
4. What risks and benefits, in terms of plutonium proliferation, might be associated with large-scale deployment of this technology in the future?

Throughout the history of this program, the development of an advanced reactor system for large-scale nuclear power generation has consistently been an overriding goal. However, that goal has not been put forth as primary in recent program justifications. As such, this OTA paper does not address the role of advanced reactors in future energy supply scenarios, the risks and benefits of nuclear power in general, or the advantages or disadvantages of this particular technology in terms of the future of nuclear power.[2]

SUMMARY OF ALMR EVALUATION

OTA's analysis shows that the DOE ALMR project is clearly in the research phase and, as such, cannot provide conclusive results regarding its potential for newly identified uses other than power production. The following summarizes OTA's analysis.

I Disposing of Weapons Plutonium

ALMR technology is one of several advanced reactor or converter systems that theoretically could convert substantial portions of a given amount of plutonium to other fission products by processing the materials through the system repeatedly over a long period. In one hypothetical system, for example, after fissioning, fuel would be removed from each reactor and reprocessed approximate] y every 2 years for a total of 50 years in order to destroy about two-thirds of the total plutonium material fed into the system. To deploy a working system that will perform effective y and efficiently would require a great deal more research and testing of several key components, as well as of the total system. Therefore, it is important to make sure that there is a clear and pressing need for such a capability and that the cost and time required to implement it are justified.

Plutonium isotopes can potentially be eliminated completely within the reactor of a future ALMR systems Thus, according to ALMR supporters, it should be favored over options that would simply produce a material with difficult-to-extract plutonium still in it. This distinction, however, becomes less important when one considers the fact that plutonium exists in all spent reactor fuel currently stored worldwide. Also, even though its percentage is small, the total quantity of plutonium now contained in all spent reactor fuel is much larger than the current stockpile of plutonium extracted from weapons. This fact has led some researchers to take the position that it is more important to put weapons plutonium into a form that is as proliferation-resistant as spent fuel as soon as possible, than it is to wait (perhaps many decades) to prove the effectiveness of a system such as the ALMR, which may be able to eliminate it.

The Department of Energy and other responsible agencies are currently developing policies and strategies with regard to the disposition of weapons plutonium. These policies will probably put a high priority on methods that can be implemented quickly to control weapons-usable material and make it more resistant to proliferation. Most policymakers recognize the urgency of dealing with materials that are now in the former Soviet Union and would also put a high priority on methods that could be implemented quickly there.

Given the above priorities, the ALMR technology would be less appropriate for plutonium disposition than more near-term technologies that would not require as long a development time (such as mixing with high-level waste and vitrification or fissioning in existing light-water reactors). However, if a policy is adopted at some future date that favors complete elimination of plutonium in all forms, ALMR technology has the potential to be one of several options that could be evaluated after more development work has been done.[4]

[2] For an overall assessment of the relative merits of this and other nuclear reactor technologies for future energy supply, see U.S. Congress, Office of Technology Assessment, *Energy Technology Choices: Shaping Our Future*, OTA-E-493 (Wash ington, DC: U.S. Government Printing Office, July 1991).

[3] It should he noted, however, that current ALMR reactor designs must always maintain some amount of plutonium within the reactor core in order to function and that this material w III remain even after many decades of operation.

[4] The other elimination options, advanced reactors and converters, are discussed in references 27 and 48.

Processing Spent Reactor Fuel

Current difficulties with progress toward an underground repository for spent fuel from commercial nuclear reactors have led proponents of the ALMR to suggest that this technology could be used to process spent fuel and thus make it more suitable for repository disposal. With technical additions for handling spent fuel, ALMR technology could potential y reprocess the spent fuel rods and, over many cycles, transform the actinides (uranium plus elements with higher atomic weights) to other materials. If all actinides were removed, proponents claim that the remaining waste would have to be isolated and contained for no more than a few centuries because the actinides are elements with very long half-lives that require repository integrity for tens of thousands of years or longer.

The above claims of complete actinide removal and transformation, however, are somewhat uncertain at the current stage of ALMR development. Less work has been accomplished on this aspect of the technology than on most other aspects. Also, although actinide removal is theoretically feasible, in practice it would add many more fission products to the waste stream. Some of these products also have long half-lives (equivalent to or greater than plutonium). Until more complete design analysis and testing work is done, it is not clear whether ALMR technology can offer much of an advantage, if any, to the commercial nuclear waste management dilemma. In addition, problems in establishing a nuclear waste repository may not be solved with purely technical approaches. A long history of public policy and regulatory issues related to repository planning and siting has dominated technical issues in the past and will probably continue to do so in the future.

Another proposed advantage of actinide (particularly plutonium) removal from spent fuel is that material suitable for weapons would thus be destroyed. Since the plutonium present in small quantities in all reactor spent fuel does present some level of proliferation risk, removing it could alter that risk. Recent studies have discussed the risk and approaches to managing it (26, 27). Whether ALMR technology has a place in nonproliferation strategies with regard to the processing of spent fuel will depend on comparisons with other approaches and will need to be evaluated in an international context because all countries with nuclear reactors have some spent fuel that requires management.

Processing Other Radioactive Wastes

The ALMR has also been proposed for processing certain radioactive wastes that cannot be stored or treated safely with any existing technologies. In particular, DOE has a large inventory of special spent fuel assemblies, some of which are stored under marginal conditions and require treatment or packaging to ensure adequate protection for the future. Parts of the ALMR technology may be suitable for processing such wastes, but more analysis will be needed to match the existing problems with the capabilities of the system. Very little research on this application has been conducted to date.

Another issue that requires further exploration and development is the question of what additional types and volumes of wastes from a total ALMR system may be generated that will need treatment, storage, and disposal, On the one hand, it may be possible with careful and efficient design to minimize waste. On the other hand, each step of a complex process can create its own waste stream. While an overall goal of the ALMR system is to eliminate long-lived radioactive actin ides from the waste stream, new fission-products and wastes will be generated. A more complete determination of the wastes streams produced by this technology must await the results of prototype testing.

Risks and Benefits in Terms of Plutonium Proliferation

Developers of the ALMR technology have worked to create technical barriers to prevent the diversion of weapons material that would be present within the reactor and the fuel reprocessing systems. However, critics of the program continue to stress that any technology that concentrates and separates plutonium would be a proliferation concern because it could be modified, once developed, for weapons purposes. Although technical barriers incorporated in the ALMR design may prevent material diversion when adequate inspection systems and controls are in place, they may not suffice to deter a state or a group that did not honor safeguard agreements, Most experts agree that any separated plutonium from reactors could be used to produce weapons. Whether or not the ALMR technology is proliferation-resistant thus depends more on its deployment, control and success of outside inspection, than on the technology itself.

If the ALMR technology were developed and then exported to a number of other countries, the United States should be concerned about adequate control of plutonium to prevent its diversion for weapons. Even if the system were designed to be a plutonium consumer, it would not be mechanical-1 y difficult for an owner with technical expertise to convert it to a "breeder" (plutonium producer). The difficulty of converting the ALMR system from a '"burner" to a "breeder" is related to the stage of its development and whether the conversion possibility was a factor in the initial design of a reactor. Since the technology is currently in the R&D stage, one could easily complete a specific design to fit requirements for either an easy or a difficult conversion. Nevertheless it would be difficult or impossible to design a reactor core that could be guaranteed to not work as a plutonium breeder. In addition, the ALMR technology has certain components such as a hot cell that could be used to support other equipment to concentrate, separate, and purify plutonium. Technical systems could be built, and inspection procedures adopted, to monitor operations and protect against proliferators, but the technology itself could not be a guarantee against misuse.

Compared with other older technologies that have been used to reprocess spent reactor fuel and to separate plutonium,[5] the ALMR system may offer more proliferation advantages because of technical barriers that could be designed into the system. However, these possible advantages must be weighed against the risks of widely deploying systems that could be later modified if the owners had the proper technical capability and weapons-building motives.

CONCLUSION

In summary, ALMR technology will not be available for application to plutonium disposition for many years. Substantial research, development. and testing work is needed to demonstrate the performance of specific portions of the total system necessary for fuel reprocessing and waste handling. Even though ALMR technology has potentially beneficial features such as the elimination of plutonium isotopes, concerns about possible proliferation problems still have to be resolved. Whether the development of this technology should be pursued also needs to be considered in the context of plutonium disposition policy objectives as well as overall energy policy. Any subsequent development work on ALMR technology would benefit from clearly stated policy goals and specific objectives by which to measure future accomplishments.

[5] Such as the PUREX system, which is a chemical separation process commonly used in producing weapons materials and in strew commercial operations in France and the United Kingdom.

History of Liquid Metal Reactors in the United States 2

Today, U.S. commercial nuclear power reactors are based on a design known as the light-water reactor (LWR). In this design, uranium oxide-based nuclear fuel is used once and then prepared for disposal. Although not commercialized in this country, other reactor designs continue to be explored and developed. One such design is a liquid metal reactor (LMR). This design uses metal fuel that is reprocessed after each use cycle and then fed back into the reactor as new fuel. Reprocessing is a chemical and physical process whereby new fuel is separated from the waste products. The LMR reactor was origin all y developed as a "breeder reactor" to produce excess plutonium during its operation. Breeder operation implies that the reactor and fuel reprocessing system can produce more nuclear fuel than the reactor consumes.

The liquid metal reactor concept has been under development in the United States since the 1950s. The first nuclear reactor ever to produce electricity y, the experimental breeder reactor (EBR-I) at Argonne West in Idaho that began operation in 1951, was such a system (3, 15). The Clinch River Breeder Demonstration reactor was an LMR breeder design intended to demonstrate the concept on a large scale. It was designed to use a nuclear fuel reprocessing technology known as PUREX[1] for converting its spent fuel into new nuclear fuel. The Clinch River project was terminated by Congress in 1983 because of concerns about its risks in terms of

[1] The PUREX process was originally developed in the 1940s to separate plutonium for weapons production. The process in which spent fuel is dissolved, and plutonium and other materials are separated from wastes, can also be used to produce plutonium for nuclear fuel.

ARGONNE NATIONAL LABORATORY

Argonne National Laboratory West. A *number of nuclear test facilities are located at this site, including the EBR II nuclear reactor (the domed structure in the center), and its fuel recycling facility (in front and to the right of the EBR //)*

nuclear weapons proliferation, its effects on the environment, and its economics compared with competing reactor designs.

The current advanced liquid metal reactor/integral fast reactor (ALMR/IFR) concept, begun in 1984, grew out of these earlier programs. In the last decade, this development program worked with an experimental LMR breeder reactor EBR-11 at Argonne West to conduct safety tests, including simulated accidents involving loss of coolant flow; to test experimental ALMR/IFR nuclear fuels; and to develop a new type of nuclear fuel reprocessing known as pyroprocessing.

Reprocessing of spent nuclear fuel to recover plutonium and other nuclear materials for making new fuel is inherent to breeder reactors. Breeder reactor operation uses some form of spent fuel reprocessing to separate new nuclear fuel from waste nuclear fission products. Various nuclear fuel reprocessing technologies have been developed. PUREX reprocessing was pursued in the first decades of breeder power reactor development. PUREX reprocessing of commercial nuclear reactor spent fuel produces a "civilian" grade of plutonium that can nevertheless be used to make nuclear bombs.[2] During the 1970s the United States abandoned commercial PUREX plutonium reprocessing plans after a long debate over the merits and risks of developing a commercial plutonium-based nuclear power industry. The debate centered on several issues, including the environmental risks associated with the proposed nuclear fuel reprocessing cycles and expansion of the industry; the economics of plutonium reprocessing and fuel recycle; and the potential impacts of an expanded plutonium economy on international security with respect to nuclear weapons proliferation. The debate became part of the 1976 presidential campaign agenda, and in April 1977 the Carter Administration called for an indefinite deferral of U.S. programs aimed at commercialization of the plutonium fuel cycle, including spent fuel reprocessing (8, 9).

THE PRESENT ALMR/IFR CONCEPT

Researchers at Argonne National Laboratory and General Electric (GE), who together are developing the present ALMR/IFR concept, have attempted to address the earlier objections to LMR breeder reactor reprocessing systems. Some potential advantages claimed for the present ALMR/ IFR concept include the ability to:

- supply a significant portion of future worldwide energy needs, through wide deployment eventually as a plutonium breeder reactor fuel reprocessing system;
- eliminate U.S. and Russian surplus military plutonium while producing electricity;
- provide superior nuclear proliferation resistance and acceptable nuclear material safeguards, compared with the standard plutonium fuel reprocessing and separation technology (PUREX), thereby allowing export (with safeguards) to other nations:

[2] Civilian and military forms of plutonium differ merely in the concentration of the plutonium isotope plutonium-239. Military-grade material has more than 90 percent plutonium-239 and civilian grade less than 90 percent. Many consider this difference to have little significance in terms of making a nuclear bomb.

- reprocess its own spent nuclear fuel. and that from other types of nuclear reactors, into new fuel, possibly extending the cupacity or acceptability of geologic repositories and easing relevant repository licensing and safety concerns by eliminat ing some of the long-l ived radionucli des: and
- operate more safely than existing LWR systems due to fundamental physical and design differences.

These claims have not been fully demonstrated or proven at the current stage of development of this technology. However, they are used to justify continuing development because, if they were demonstratrated, they would offer considerable benefits.

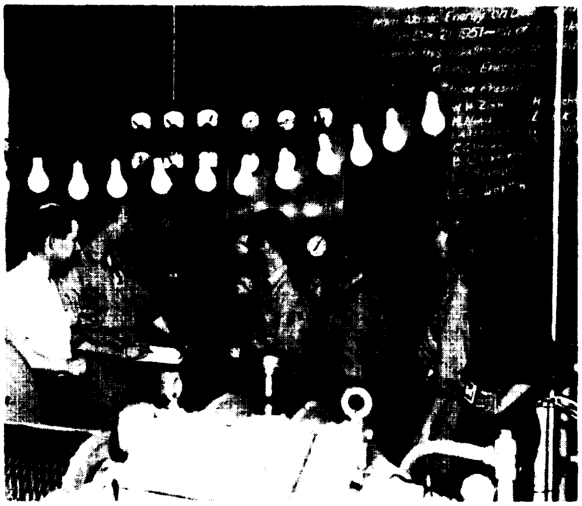
Goals of the ALMR/IFR Program

The emphasis of the ALM R/IFR and its predecessor research and developmen(programs has been adjusted in response to certain domestic and international political developments. As originally conceived of four decades ago. LMR technology meant a plutonium breeder nuclear reactor (producing more plutonium fuel than it consumed) using PUREX nuclear fuel reprocessing for the production of electricity. After the United States abandoned the commercial izat ion of breeder reactors and PUREX reprocessing in the 1970s because of concerns about plutonium proliferation, environmental impacts, and costs, ALMR/IFR developers conceived of a new fuel reprocessing technology claimed to involve less proliferation risk than the earlier PUREX technology. Nevertheless, electricity production remained the primary goal for justifying the program. During the last 5 years, however. the ALMR/IFR concept began to be promoted more as a method to reprocess and transform spent nuclear fuel from commercial LWRs so as to make it more acceptable for disposal in geologic repositories, such as the still incomplete Yucca Mountain repository in Nevada.[3] After 1991, when arms reduction agreements between the United States and the former Soviet Union appeared likely to produce significant quantities of surplus military plutonium, developers of the ALMR/IFR concept emphasized its potential to eliminate this plutonium by consuming it as a nuclear fuel to make electricity.

Most recently, ALMR/IFR developers have again refocused on the potential of the technology to eliminate plutonium (and other actinides) in spent nuclear fuel by reprocessing it into new ALMR/IFR fuel (and waste fission products). However, this time the rationale is not so much that it would help the geologic repository program, but rather that as long as plutonium exists even in spent nuclear fuel, it remains a potential nuclear weapons proliferation risk. The ALMW/ IFR concept, developers argue, might eliminate that risk. The technology was renamed the "ALMR actinide recycle system" to reflect this change of emphasis.

One proposal for the ALMR/IFR specifically examined in the recent Office of Technology Assessment (OTA) report *Dismantling the Bomb and Managing the Nuclear Materials was* its use for the disposition of surplus military plutonium. Its designers have promoted it as a means to transform surplus weapons plutonium into fission products that could never be turned back into a nuclear bomb. The OTA report concluded that although the ALMR/IFR system was designed as a plutonium producing breeder reactor it could be operated as a net plutonium consumer. However, some limitations of the ALMR/IFR concept for

[3] Geologic repositories are deep, excavated underground vaults constructed for the purpose of permanently containing nuclear wastes. The Yucca Mountain site in Nevada is being evaluated by the Department of Energy for its suitability as a geologic repository for spent nuclear fuel from commercial reactors. In December 1987, Congress amended the Nuclear Waste Policy Act of 1982 mandating that Yucca Mountain be the only site evaluated for a national nuclear waste repository. Public opposition, management problems, technical uncertainties, and regulatory difficulties have delayed the evaluation process. The date at which a geologic repository may be completed and licensed to accept high-level waste remains uncertain.



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Electricity was first generated with the EBR 1 (Experimental Breeder Reactor 1) in 1951 Research with this system was in part the basis of the EBR II and the current ALMR/IFR design.

plutonium disposal noted in the OTA report include the following:[4]

- It would require many cycles of plutonium reprocessing over many decades to completely fission and destroy a significant portion of surplus military plutonium, compared with other possibly more rapid disposal methods such as vitrification.[5]
- The plutonium reprocessing required for complete destruction of surplus military plutonium is a transformation and not a disposal method. It would change one type of waste (plutonium) into another type of waste (highly radioactive fission products) that would still require treatment and disposal in facilities that are not yet available in the United States (a problem in fact with any radioactive waste disposal concept).
- The licensing and change in national policy involved in the act of deploying plutonium-fueled nuclear power reactors with plutonium reprocessing could be expected to be difficult in the United States, which abandoned this technology in the mid-1970s because of economic and proliferation concerns.
- It would not be economical to develop such a reactor system solely for disposal of surplus military plutonium. Selection of this option could make sense only as part of a larger national decision to turn to a plutonium breeding/reprocessing nuclear energy program.
- Developers of the ALMR/IFR concept envision many facilities operating as breeder reactors deployed in the21 st century as the next generation of U.S. nuclear power reactors. In this scenario, the amount of plutonium available from dismantled nuclear warheads would be relatively minor compared with the amount of plutonium that would be cycled through these reactors.

Selective emphasis on a single capability or function of the ALMR/IFR concept, while ignoring its other features, has made it difficult for those not intimately involved to evaluate, criticize, or even understand the program. Therefore, for the purpose of the present study, the ALMR/IFR system is looked at from the broadest perspective. It is evaluated as a system containing a nuclear reactor capable of operating as a plutonium breeder, a nuclear fuel reprocessing and fabrication (pyroprocessing) system, a nuclear waste handling system, and a system for reprocessing existing spent fuel from conventional U.S. commercial LWR into new ALMR/IFR nuclear fuel.

In addition, the present study looks at the timeliness of the ALMR/IFR technology. That is, given the early development status of the program,

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[4] For a more complete explanation of these Findings, see U.S. Congress, Office of Technology Assessment, *Dismantling the Bomb and Managing the Nuclear Materials* (Washington, DC. U .S. Government Printing Office, 1993). Some of the advantages claimed by the developers are listed on the following pages.

[5] ALMR/IFR promoters point out that the technology could provide more rapid disposition by using the fuel made from weapons plutonium for a very short period and removing it for storage and subsequent complete burning in the future. The short fuel use would "spike'" the material by making it radioactive, although less radioactive than the fully used up fuel. This strategy would also be appl icable to any reactor-based disposition; for example, after conversion to MOX (mixed uranium and plutonium oxide) the fuel could be used briefly in already available conventional reactors to achieve the "spiked" fuel effect.

what long-range problems in energy production or waste handling might it be appropriate for the ALMR/IFR technology to address?

Previous Analyses of the ALMR/IFR Concept

A number of studies have examined the use of nuclear reactors, including the ALMR/IFR, to dispose of plutonium from dismantled U.S. and former Soviet Union nuclear weapons or from spent nuclear fuel. These studies were carried out by the Office of Technology Assessment, the National Research Council Committee on International Security and Arms Control, the General Accounting Office, the RAND Corporation, and the Department of Energy (27, 37, 46, 48, 50), Although each study approached the issue from a unique perspective, they reached many similar conclusions.

All concluded that long-term plutonium disposition will be lengthy, complex, and costly. In addition, short-term plutonium storage will be required regardless of the ultimate disposition option selected. The most available long-term options are either conversion to mixed-oxide fuel for use in existing, proven, light-water reactor designs without nuclear fuel reprocessing, or disposal as waste, for example through vitrification. Any disposition option will stretch over decades and is likely to involve costs rather than net economic benefits. Although all options involve some unresolved issues and risks of uncertain magnitude, these studies concluded that the development of advanced reactors for plutonium disposition would involve the highest costs and greatest uncertainties.

Description of the ALMR/IFR Program 3

The Department of Energy (DOE) has been funding the development of an advanced liquid metal reactor under a program within the Office of Nuclear Energy. Recent budgets for this program were between $40 million and $43 million per year for FY 1992 and 1993, and $30 million for FY 1994. Most of the budget has been directed toward research work at the Argonne National Laboratory. During FY 1992 and 1993. some $10 million per year was directed toward research at the General Electric Company (GE).

The current DOE concept of the advanced liquid metal reactor/ integral fast reactor (A LMR/IFR) system includes a liquid metal-cooled nuclear reactor and associated nuclear fuel reprocessing, manufacturing. and waste processing facilities. The system combines many discrete components operating together at a single site. The complete system can be divided into three major parts:

1. an advanced li quid metal reactor.
2. a fuel reprocessing system for transforming ALMR spent fuel into new fuel and processing its radioactive waste fox- disposal, and
3. alight-water reactor (LWR) spent fuel reprocessing system for the recovery of plutonium, uranium, and related act in ides from the spent fuel from conventional U.S. nuclear reactors to make new ALMR/IFR nuclear fuel.

Figure 3-1 illustrates these major components and shows the stage of development for each. For example, the current reactor part of the test system is a prototype that has been operating in various tests for more than 30 years. Many of the fuel reprocessing components. such as the electrorefiner, have been tested but have yet to be tested as a prototype system. Many of the waste and spent fuel processing components are still in the design stage.

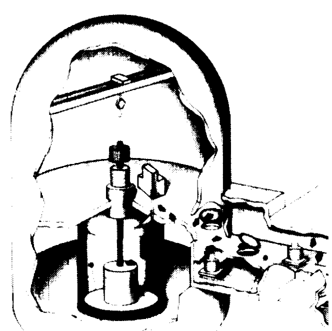
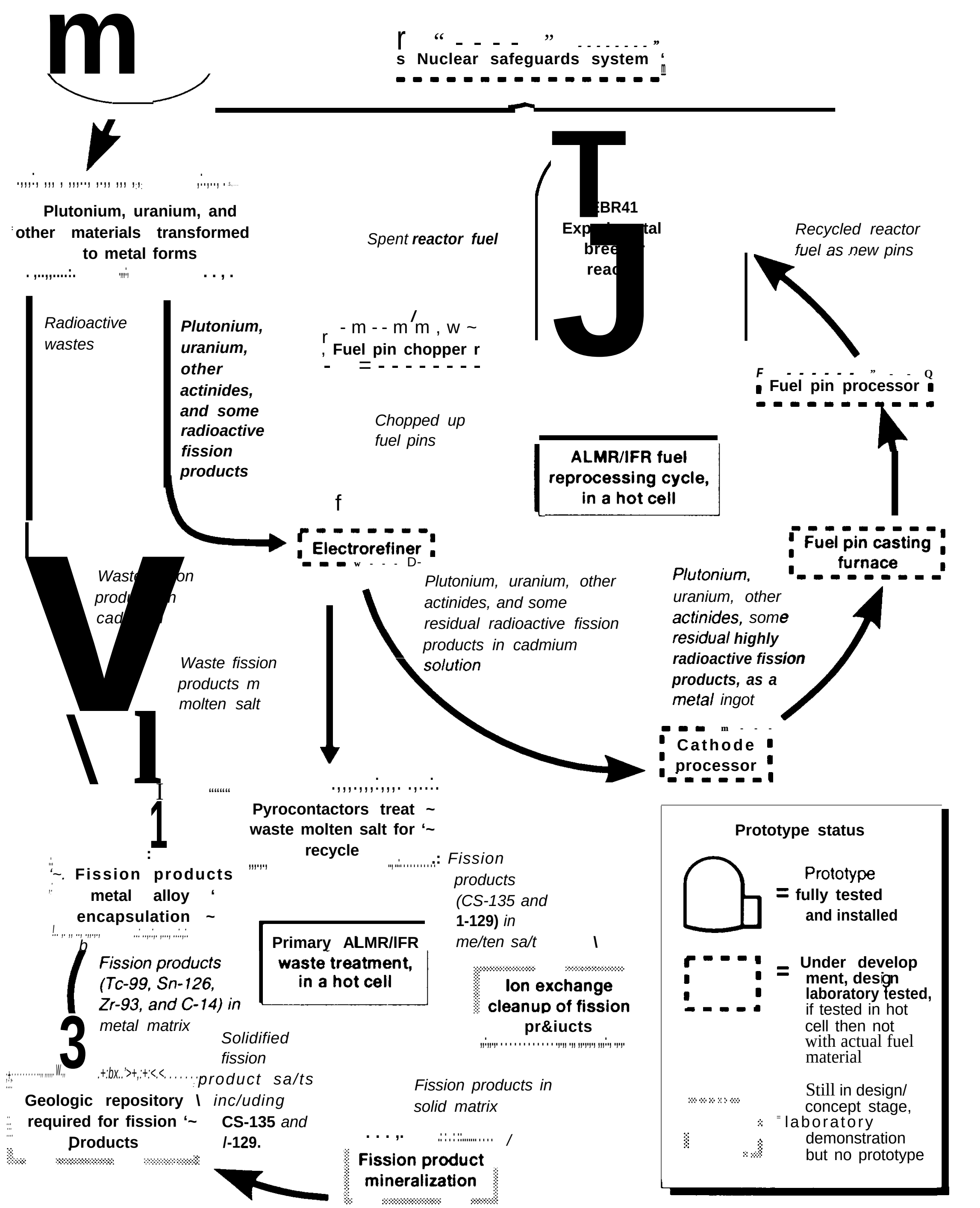


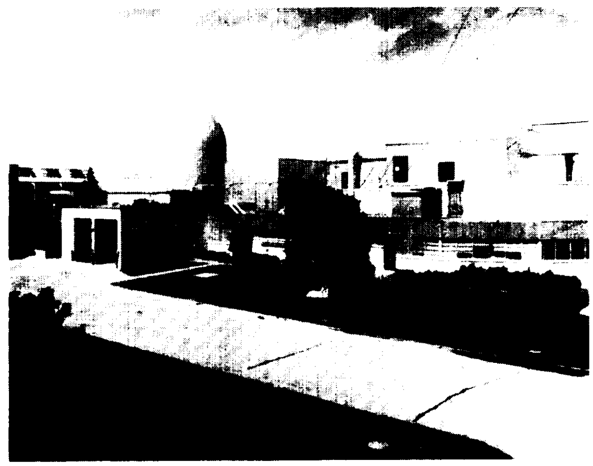
FIGURE 3-1: Planned ALMR/IFR Prototype at Argonne West, Idaho



NOTE The system would involve many interlinked components, including a nuclear reactor and facilities for fuel reprocessing and fabrication, for reprocessing conventional reactor spent fuel into new ALMR/IFR fuel, and for handling the resulting nuclear wastes

SOURCE Argonne National [Laboratory

Argonne National Laboratory and GE are partners in research and development for the ALMR/IFR program. Argonne has taken the lead in developing the ALMR metal fuel reprocessing technology, while GE is focusing on developing the full-scale nuclear reactor. At present, the 30-year-old Experimental Breeder Reactor II (EBR-II) at Argonne West is serving as a prototype reactor for testing ALMR/IFR nuclear fuels (43). However, since the EBR-II is scheduled to be decommissioned at the end of 1994, its role in ALMR/IFR prototype development will be ending. DOE partly funds the GE reactor design project—at about $10 million per year over the last few years (43). GE also takes an active role in the ALMR/IFR fuel reprocessing development, via regular-meetings and consultation with Argonne National Laboratory researchers.



ARGONNE NATIONAL LABORATORY

The EBR-II and fuel processing facility at Argonne West are prototype scale facilities. The reactor portion (left) has been in operation for several decades.

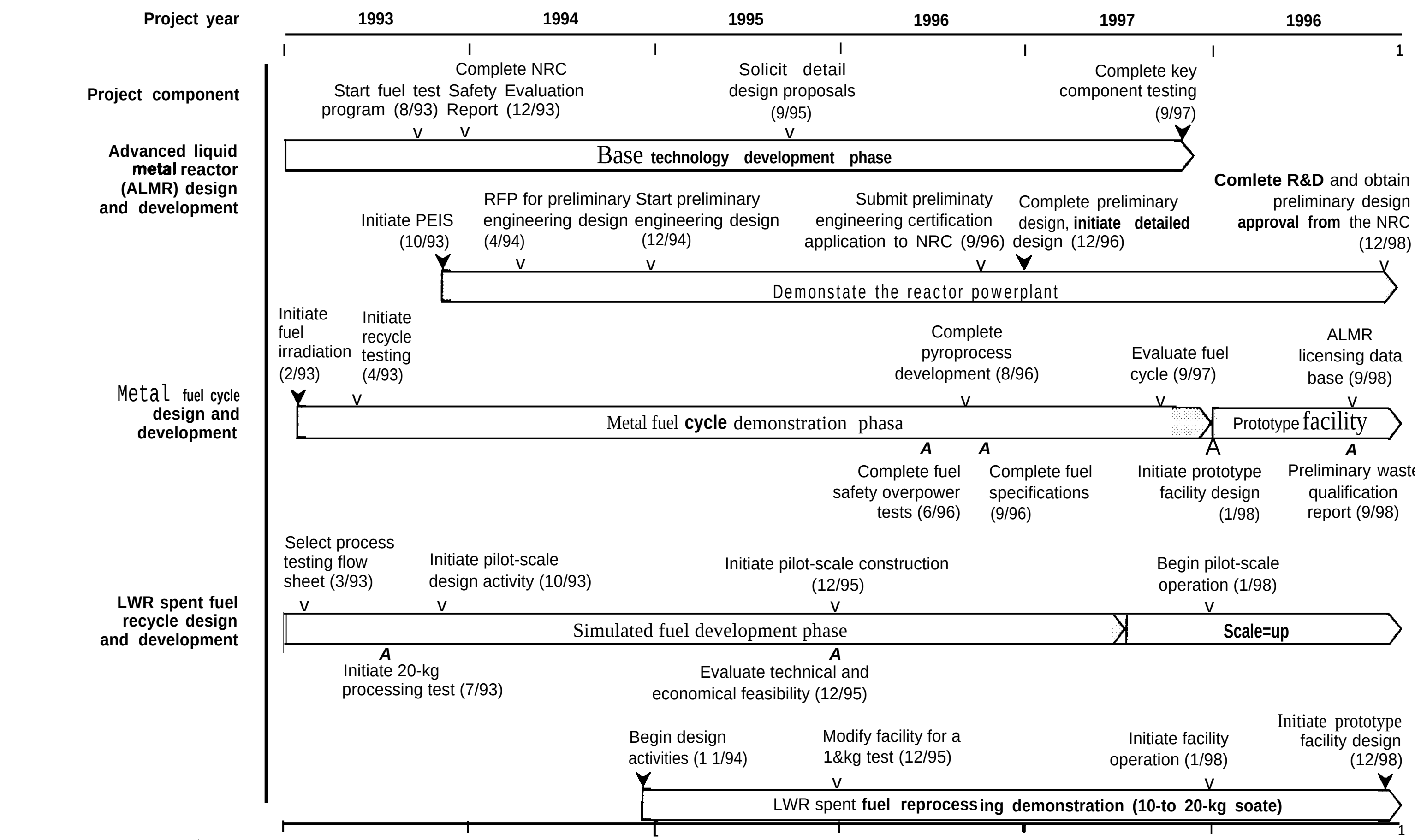
Figure 3-2 shows the 5-year schedule announced by DOE in 1991 for the development of a prototype ALMR/IFR at Argonne West(51). The total costs (shown by year and including nongovernmental contributions) over 5 years were projected at the time as $976.4 million.

Although the exact dates will change as work proceeds, the status of development of each component shown in figure 3-1 and the schedule shown in figure 3-2 illustrate that substantial developmental work remains to be done, and many of the individual components are in only the concept or early prototype stage. Some components have been demonstrated in the laboratory, but prototypes have not yet been constructed or tested. Thus any description of the ALMR/IFR system must be based partially on plans, rather than on actual hardware. This description also will have to be revised as the system is designed and developed. The schedule shown in figure 3-2 is for a prototype facility only (which was planned to be constructed at Argonne West), not for full commercialization of the technology. Although this schedule is already out of date, it serves as a general indication of the amount of development work ahead. It will require revision, for example, after the recent decision to suspend development of the nuclear reactor portion of the program and concentrate only on development of the prototype fuel reprocessing system (3).

FUTURE FULL-SCALE COMMERCIAL DEVELOPMENT

If the planned research and development work, followed by completion of a prototype, is completed by Argonne and GE, full-scale commercial development using part or all of this fuel cycle may be carried out by a private sector multiorganization team. Using this assumption, GE has projected the full-scale ALMR system as a 1.866-gigawatt electric ALMR/IFR modular design plant that could include an ALMR/IFR metal fuel reprocessing facility with a capacity of 22 metric tons per year. Alternative] y, a centrally located facility with a capacity of 180 metric tons per year might support eight separate ALMR plants (44). The complete facility could also include a 2,800-metric-ton-per-year LWR spent fuel processing and conversion facility (12, 34, 42). High-level and low-level waste processing facilities would be colocated with the reactor and fuel reprocessing facility. One reactor design proposed by GE would use a nuclear fuel breeding ratio of 1.05 (i.e., for every pound of plutonium consumed during a fuel cycle, 1.05 pounds of new plutonium would be produced) and would also have the ability to operate at a range of ratios from 0.6 (thus

FIGURE 3-2: Proposed 5–Year Schedule and Projected Costs for a Prototype ALMR/IFR



Yearly cost ($ million)	1993	1994	1995	1996	1997	1996
ALMR	8.8	31.5	47.7	101.0	151.0	137.0
Metal fuel	26.4	32.6	53.7	56.9	60.1	62.2
LWR reprocessing	6.5	18.5	19.5	30.0	30.0	30.0
Nongovernment contribution	9.5	12.0	13.5	10.0	15.0	13.0
Total	**51.2**	**94.6**	**134.4**	**197.9**	**256.1**	**242.2**

NOTE Although it IS out of date the schedule shows the amount of developmental work that remains undone Any analysis of the ALMR/IFR system WilI require revision as the system IS designed developed, and deployed

KEY NRC = Nuclear Regulatory Commmission PEIS = programmatic environmental impact statement RFP - request for proposals

SOURCE U S Department of Energy, 5-Year Plan, 1993 consuming plutonium) to 1.23 (thus breeding plutonium) (34).

As of the end of 1993, GE projected schedule was as follows" (34):

- by 1996, complete technical feasibility and economic potential studies, as well as key features test and qualification phases;
- by 1999, complete both a concept demonstration and metal fuel qualification, and a components and subsystems test phase;
- by 2010, complete design certification; and
- after 2010, begin commercial deployment.

GE also projected that reprocessing LWR spent fuel could provide a source of startup plutonium fuel necessary for commercial-scale deployment (34, 42). The low-enriched uranium that will be simultaneously recovered from the reprocessed LWR fuel might either be put back into existing LWRs or into recycled AL MR/IFR fuel as a fertile material for breeder operation, or be disposed of as actinide waste in a repository. As an alternative approach, GE projected the full-scale AL MR/IFR system also to be capable of using a more conventional mixed uranium-plutonium oxide fuel (MOX) without electrorefiner reprocessing (42, 45).[1]

The commercial full-scale ALMR as conceived of by GE is a breeder-capable nuclear reactor that uses liquid sodium as a coolant, and a metal nuclear fuel containing plutonium and uranium. The full-scale GE ALMR design is projected to be a bank of up to six modular reactors, each generating 311 megawatts of electricity (each approximately 16 times larger than the EBR-II prototype) (34). With nuclear fuel reprocessing the system would be capable of operating as a breeder reactor (making more plutonium than consumed). This design has not yet been built. By comparison, conventional LWRs used for commercial power generation today in the United States are water cooled, use uranium oxide nuclear fuel, and do not reprocess their spent fuel.

The ALMR/IFR system has generally been presented as easily convertible between plutonium breeding and burning. The full-scale ALMR system envisioned by GE is designed specifically to be converted easily between breeding and nonbreeding operation (42). According to its designers, "[b]y straightforward adjustments in fuel composition and arrangement, the system can be readily adjusted to meet any overall fissile demand scenario, from being a rapid consumer of fissile material (conversion ratio as low as about 0.6) to a net producer (breeding ratio as high as about 1.3)"2 (14). Figure 3-3 shows across section of the arrangement of fuel elements in a full-scale ALMR reactor in the breeding and nonbreeding configurate ion. As can be seen, both configurate ions use the same total number of elements in the reactor core. Only the arrangement of fuel, the fuel type, and the presence or absence of fertile material (for breeding) are different (21).

| The ALMR/IFR Fuel Reprocessing System

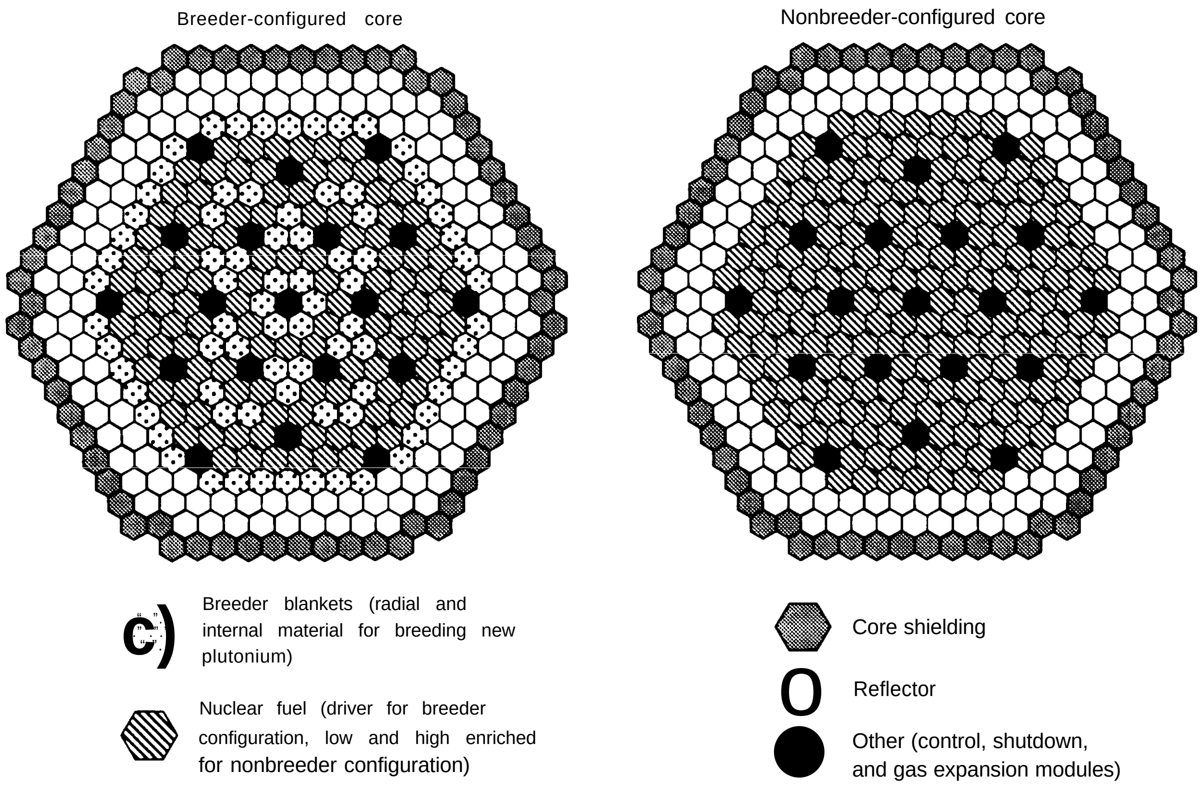
The ALMR/IFR fuel reprocessing system as currently envisioned by Argonne researchers will be a complex of equipment for handling spent fuel, chopping up the fuel elements, reprocessing to separate actinides from fission products, converting into new reactor fuel elements, inspecting and quality control, and handling and processing radioactive waste for disposal. Because of the intense radiation of spent fuel, reprocessed fuel, and

---

[1] Conventional LWRs fueled with uranium oxide will transform some of the uranium-238 (the bulk of the fuel material) contained in the fuel into plutonium as the fuel is irradiated in the reactor. This is the source of the approximately 1 percent plutonium contained in LWR spent fuel. The difference is that in LWR reactors the plutonium is left in the spent fuel for disposal. Breeder reactor operation requires that the spent fuel be reprocessed to recover the plutonium.

[2] At the end of each cycle of fuel fissioned in the reactor (approximately 18 months to 2 years), a conversion ratio of 0.6 means that about 60 percent of the original amount of plutonium in the fuel would remain, while a conversion ratio of 1.3 means that about 130 percent of the original amount of plutonium would be present.

FIGURE 3–3: Cross Section of ALMR Cores for Breeder and Nonbreeder Configurations



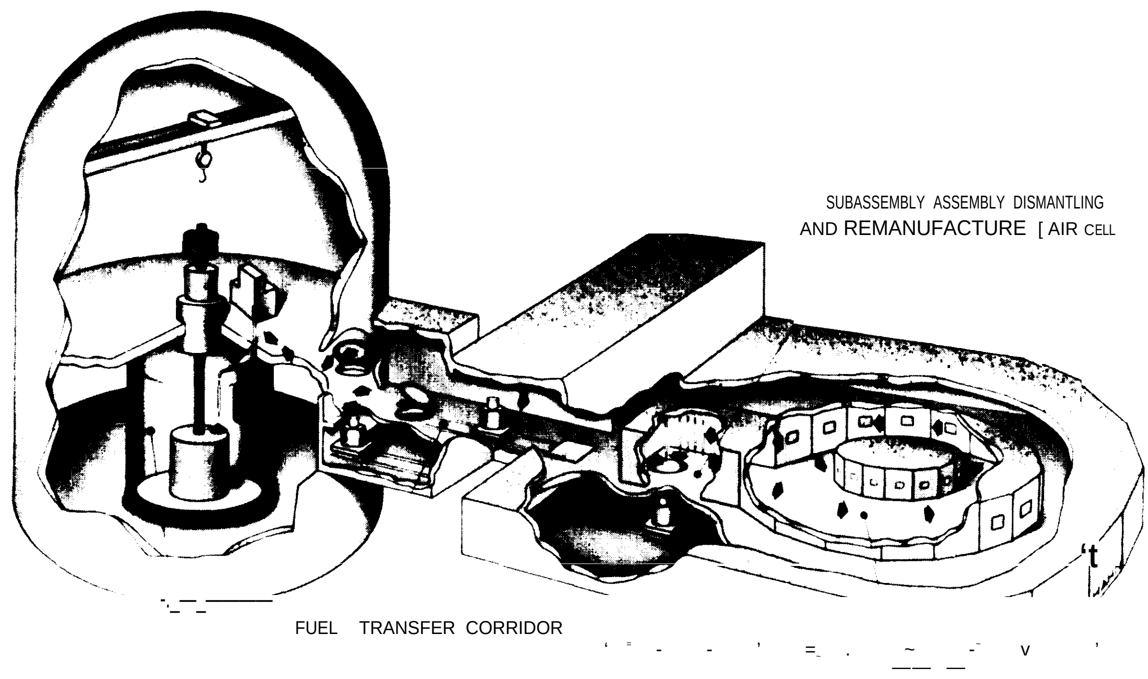
SOURCE Magee (GE), 1993

waste from the reprocessing of spent fuel, all of these operations would have to be carried out in a remotely operated hot cell.

Remotely Operated Hot Cell

The hot cell is an enclosed area surrounded by heavy shielding to protect workers against the intense radioactivity present from the fission products in spent and new reprocessed ALMR/IFR nuclear fuel. In addition, because of the extreme chemical reactivity with air or water of ALMW/IFR fuel materials and processing chemicals, processing is done in an inert atmosphere (the current prototype uses dry argon gas). Even new recycled ALMR/IFR fuel after reprocessing will contain sufficient amounts of highly radioactive fission products to require heavy shielding and remote manipulation by robotics or remotely operated manipulators. For radiation protection, a hot cell has walls made of several feet of concrete and 4-foot-thick special radiation-shielding glass windows for viewing. All operations would be done with remote manipulators or by automation. After startup with radioactive materials, no human would enter the hot cell.

Argonne researchers are in the process of transforming an existing hot cell facility at Argonne West for this purpose. The hot cell was originally built as part of the demonstration of an earlier version of the current design, with the EBR-II as part of a breeder reactor system integrated with onsite molten salt metallic fuel reprocessing from 1964 to 1969 (12, 31). It consists of two hot cells, one with an air and the other with an argon atmosphere, and a passageway connecting them to the EBR-II reactor building for transfer of spent fuel



ARCONNF NATIONAL LABORATORY

Diagram showing plans for converting the existing EBR II and Fuel Cycle Facility to an ALMRIIFR prototype system The system would contain the nuclear reactor (EBR II on the Ieft) and the fuel reprocessing facility (rfght).

containers. Argonne researchers expect that the ALMR/IFR demonstration equipment to be constructed and installed in the hot cell will be of a scale appropriate for a full commercial-size ALMR/IFR installation.

Electrorefiner Fuel Reprocessor

The electrorefiner, now under development at Argonne West, would be used to dissolve, reprocess, and divide spent fuel from the reactor into new fuel material and spent fuel fission products (see box 3-1). With some process modifications, the electrorefiner might also be used to reprocess spent fuel from existing commercial U.S. light-water reactors, Irradiated fertile (breeding) elements from an ALMR breeder configuration would be similarly processed using this equipment (14). Because of the intense radioactivity of the fission products, the electrorefiner must also be operated remotely in the hot cell.

The electrorefiner is a key part of the ALMR/IFR nuclear fuel reprocessing cycle, but it is still in the early stages of development. A full-scale prototype electrorefiner is being readied for testing with remote operation, before installation in the hot cell at Argonne West. This installation is expected to be completed in 1994(31). This prototype has yet to be tested with actual spent fuel material, although a similar unit has been tested with unirradiated fuel (17). *The* fuel element chopper for chopping the spent fuel pins has been installed in the hot cell for testing. The first test will be a qualification step that involves chopping metallic sodium-filled dummy fuel elements.

BOX 3-1: The Electrorefiner Fuel Reprocessor

The electrorefiner will be at the heart of both the ALMR/IFR fuel reprocessing technology and the possible reprocessing of spent light water reactor (LWR) fuel into new ALMR/IFR fuel. It WIII be a vat heated to 500°C (about 930°F), filled with molten mixture of lithium and potassium chloride electrolyte that contains both cathode and anode electrodes, resting above a liquid cadmium phase (see ftgure 3-4). The fuel IS mechanically chopped up, placed in the anode basket, and then broken up through electrochemical action to allow the plutonium, uranium, and other actinides, along with some fission products, to be dissolved in the molten salt. The chopped stainless -steel fuel cladding is not dissolved but IS left behind in the anode basket (16). Other materials from the chopped spent fuel that are less soluble in molten salt simply fall into the molten cadmium phase located below the molten salt phase. Selective distribution to the molten salt, rather than the liquid cadmium, results in the upper phase containing most of the highly electropositive fission products, including alkali metals such as cesium, alkaline earths such asstrontium, and some rare earths (Ianthanides) (figure **3-4)** Noble metal fission products, including ruthenium, rhodium, molybdenum, palladium, technetium, and zirconium, and more rare earth (Ianthanide) fission products along with zirconium from the fuel alloy move to the lower cadmium pool ***(14).***

After the spent fuel is electrochemically dissolved, passage of an electric current through the iron electrode causes the bulk of the uranium dissolved in the molten salt electrolyte from the spent fuel to become deposited as a metal on the iron cathode. ALMR/IFR designers hope to recycle this uranium to make new reactor core or fertile material (breeding) elements, Next, the plutonium, remainder of the uranium, and other actinides such as neptunium, americium, and curium from the dissolved chopped fuel are transported electrochemically to asecond, smaller liquid cadmium pool cathode contained in a ceramic crucible immersed in the electrorefiner molten salt (14). Some rare earth (lanthanide) fission products also inevitably end up codeposited with the actinides in this cadmium cathode, Both the salt and the cadmium phases would accumulate highly radioactive fission products and would require periodic processing to remove these waste products for disposal.

An electrorefiner large enough to support fuel reprocessing for a commercial-scale reactor such as the full-scale ALMR concept would be about 1 meter in diameter and would contain 1,000 kg of cadmium and 500 kg of salt (14). Argonne researchers expect that fuel reprocessing wiII be done in batches containing about 10 kg of uranium and 3 to 5 kg of fissile materials (mostly plutonium) (13).

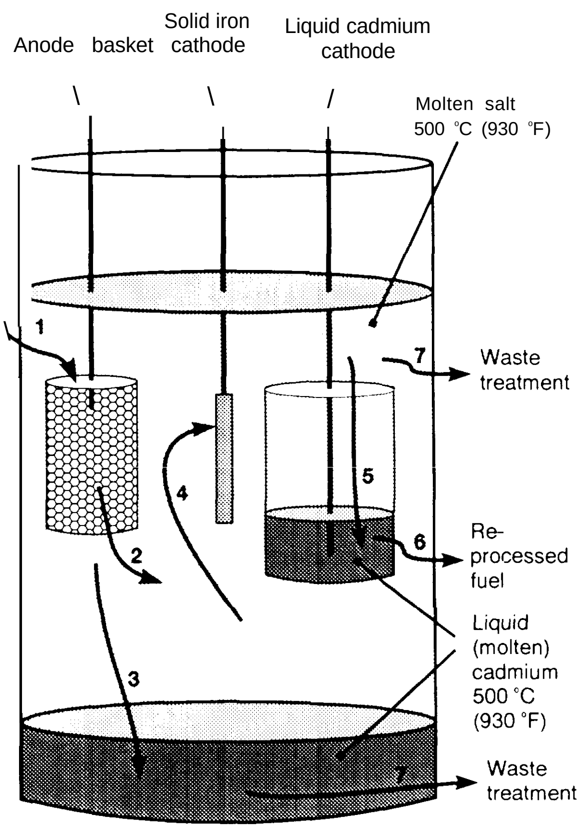
To adapt the electrorefiner processor LWR spent fuel reprocessing, the LWR spent fuel, which IS composed of the oxides rather than the metallic forms of uranium, plutonium, other actinides, and fission products, must first be chemically reduced to the metal (16), This reduction can be accomplished by treating the chopped LWR spent fuel with Iithium metal m the molten salt solution (28). After conversion to the metal form, the material would be collected from the bottom of the molten salt bath and transferred to the anode basket of the electrorefiner, where spent ALMR/IFR fuel IS Introduced as described above, There it too could be processed into new fuel

The Cathode Processor

One of the key steps in the electrorefiner involves concentrating actinides collected at the liquid cadmium cathode (see figure 3-4). After processing, most of the actinides, including plutonium and uranium, along with some fission products, will be deposited in a molten cadmium pool contained in the liquid cadmium cathode. This cadmium pool will then be transferred to another piece of equipment called the cathode processor. After evaporation of the cadmium (which will be recycled), the plutonium, uranium, other actinides, and remaining rare earth (lanthanide) fission products will be recovered as a metal ingot at the bottom of the cathode processor.

This ingot will contain up to 70 percent plutonium and 30 percent uranium and other actinides, as well as a minor amount of rare earth (lantha-

FIGURE 3-4: Diagram of Current Electrorefiner Design



NOTE The electrorefiner would reprocess spent ALMR/IFR metal fuel into new fuel and highly radioactive waste fission products in a hot cell The operations described here have not yet been conducted with actual spent nuclear fuel A similar but physically separate system is envisioned for reprocessing LWR spent fuel Into new ALMR/IFR fuel

SOURCE Argonne National Laboratory

Notes on figure 3-4

1. Spent metal fuel from an ALMR containing plutonium, uranium, and other actinides, and highly radioactive fission products, is mechanically chopped up and placed in the anode basket Chopped fuel is broken up electrochemically and its nuclear components are dissolved in the molten salt, leaving behind the old fuel cladding
2. The plutonium, uranium, and other actinides, and most of the highly electropositive fission products, are dissolved electrochemically in the molten salt This includes alkali metals such as cesium, alkaline earths including strontium, and some rare earths (lanthanides)
3. Noble metal fission products including ruthenium, rhodium, molybdenum, palladium, technetium, and zirconium are not transported electrochemically but settle as metal particulates in the molten cadmium pool at the bottom of the electrorefiner The cadmium pool accumulates radioactive waste fission products
4. Passing an electric current through the electrodes causes the bulk of the dissolved uranium to become deposited as metal on the iron cathode
5. The plutonium, remaining uranium, and other actinides, and some rare earth fission on products, are transported electrochemically from the molten salt to a cadmium cathode, made of a smaller cadmium pool in a ceramic crucible The material in the cadmium cathode is as high as 70 percent plutonium and 30 percent uranium and other actinides, and less than 1 percent rare earth fission products Other highly radioactive waste fission products accumulate in the molten salt
6. After reprocessing and separation are complete, the molten cadmium from the cadmium cathode is transferred to the cathode processor where cadmium is removed, leaving a metallicing got that will be made into new ALMR fuel
7. Fission products from reprocessed fuel accumulate in the molten salt and cadmium Periodically these must be removed, and the waste materials processed, producing a highly radioactive waste form for disposal

nide) fission products. Although the lanthanides contribute less than 1 percent of the mass, along with certain more radioactive actinide isotopes, they generate the hazardous radioactivity responsible for what the developers consider the "self-protecting" proliferation resistance of the final recycled fuel product.[3] A significant amount of the total radioactivity of the final product from the cathode processor and of the radioactive decay heat comes from the minor transuranic isotopes that are retained through the separation process (17). One estimate is that without further purification this material would be about 10,000 times more radioactive than a similar product from conventional PUREX reprocessing (56). This radioactivity also means that the cathode processor must be placed in the remotely operated hot cell. The device is currently undergoing tests for re-

3 Self-protecting proliferation resistance originally referred to the intense radioactivity due to the fission products in spent nuclear fuel that makes it lethal to handle without extensive protection. This radioactivity "protects" the material from theft or diversion. The amount of fission products in ALMR/IFR reprocessed fuel is significantly lower than in LWR spent fuel and provides less self-protecting radiation. For this reason, radioactivity from the residual actinides becomes more important for the self-protecting aspect of ALMR/IFR reprocessed fuel compared with LWR spent fuel (17).

BOX 3–2: Fuel–Pin Casting Furnace

A prototype device for casting new fuel elements IS currently Installed in the Argonne West hot cell, It consists of a series of units for converting the metal ingot from the cathode processor into new fuel pros. The fuel pin injection casting machine IS similar to existing equipment used with the experimental breeder reactor (EBR - II), except that it IS designed to be operated remotely in the hot cell. After the metal ingot has been melted in a furnace, its composition IS Intended to be adjusted by adding zirconium and uranium in proportions appropriate for new ALMR/IFR fuel. Next, the metal IS cast into new fuel pins in precision quartz molds that resemble long drinking straws (54) After inspection, the newly cast fuel IS loaded into stainless-steel cladding along with sodium metal and an inert atmosphere to make anew fuel pin. Volatilization of the radioactive actinide element americium during casting may be a problem, In one experiment casting fuel pins with minor actinides, approximately **40 percent** of the americium charge was lost during casting due in part to evaporation **(54). Currently, the quartz** molds are broken off after casting and create a waste material. Argonne West researchers have done some experiments on replacing the quartz with direct casting into azirconium sheath that could be inserted into conventional stainless-steel cladding.

Argonne researchers have not yet tested actual recycled ALMR/lFR fuel in this system. The pin casting furnace has been installed in the Argonne West hot cell, and some experiments in casting depleted uranium have been completed. Experiments are planned for 1994 to fabricate experimental uranium-plutonlum-zlrconwm (ternary) fuel elements (31). As part of the research on fuel design, a full-scale ALMR prototype fuel containing uranium, plutonium, and zirconium has been Irradiated to high degrees of fuel burn up (fissioning of total fissionable materials) in the EBR-II (54). ALMR/IFR fuel from recycled light water reactor spent fuel will contain about 20 percent plutonium and 10 percent zirconium, along with 70 percent uranium (mostly U-238) (54).

As part of the equipment required for fabricating new fuel pins for the EBR - I I, a “welder/settler” IS also being tested Argonne expects to transfer it to the hot cell so it will be available in 1994. A “vertical assembler/disassembler’” for fuel pin fabrication IS being tested as well and will be installed in the hot cell when available. A “fuel element inspection x-ray system” IS also under development.

mote operation and is expected to be installed in the Argonne West hot cell in 1994 (31).

After the metal ingot material is removed from the cathode processor, it is transferred to a fuel pin casting furnace and then to a fuel pin processor. The function of these parts is to produce new fuel rods from the processed material that will then be recycled to the reactor, to complete the entire fuel reprocessing step. Box 3-2 describes the specific operations envisaged for the casting furnace and the status of its development.

ALMR/lFR High-Level Nuclear Waste Treatment Processes

During the electrorefining reprocessing of spent fuel, fission products and other materials will accumulate in the molten salt and the bottom liquid cadmium pool (figure 3-4). Eventually, these waste products will generate excessive heat and cause unacceptable contamination (by the accumulating rare earth fission products) of the reprocessed nuclear fuel deposited in the liquid cadmium cathode (16). Argonne researchers expect that a salt load might be used for several dozen fuel reprocessing cycles before requiring treatment. The intense radioactivity from the fission products means that all waste treatment will have to be performed in the remotely operated hot cell. Waste recovered from the molten salt and cadmium would have to be disposed as high-level radioactive waste in some suitable repository. Box 3-3 describes the steps involved in waste treatment and the development status of this subsystem.

It will also be necessary for the ALMR/IFR waste processing technology to meet current and proposed high-level waste packaging and storage

BOX 3–3: ALMR/IFR High–Level Radioactive Waste Treatment

Reprocessing ALMR/IFR spent fuel will separate highly radioactive fission products that must be processed for eventual disposal The molten salt containing waste fission products and small amounts of actinides from the electrorefiner would be transferred into a processing device called a pyrocontactor There it will be treated with a uranium-cadmium alloy to reduce the residual transuranic chlorides to their metal forms (1 6) This would recover residual plutonium, uranium, and other actinides (which are returned to the electrorefiner) from the molten salt Next, the molten salt would be treated with Iithilum in molten cadmium to remove the rare earth fission products in a Iiquid cadmium phase that would be combined with the Iiquid cadmium waste stream coming from the electrorefiner (figure 3-4)

fission products still remaining in the molten salt will require further treatment to remove them Argonne researchers have performed preliminary experiments with nonradioactive fission product analogues, [1] showing how fission products remaining in the salt—Including cesium, strontium, rare earths, and Iodine 129—might be recovered by passing the molten salt through a zeolite (mineral)-based ion exchange column Two possible final waste forms (for placement in a geological repository) are under development one IS a bonded zeolite” in which zeolite IS permeated with a Iow-melting glass for mechnical strength and leach/d If -fusion resistance the second is a sodalite mineral structure formed by pyrolysis of a blended zeolite material If the development of this technology IS successful, the purified molten salt could be recycled back to the electrorefIner

FIsslon products in the molten cadmium pool from the electrorefiner, including the transition metal fission products technetium, ruthenium, rhodium, and zirconium, after reduction to their metal forms, are expected to be placed in a stainless-steel matrix and cast into a metal ingot waste form, by using the remaining nuclear fuel cladding hulls as a source of stainless steel If the development of this technology IS successful, cadmium would also be recycled to the electrorefiner

None of these processes has been tested with actual ALMR/IFR recycled fuel A single-stage pyrocontactor has been tested in a glove box, and initial flow tests with salt and cadmium have been conducted (16) A multi-stage pyrocontactor test apparatus (seven or eight stages will be required to meet target actinide recovery) IS under design Some experiments reducing rare earth salts to their metallic forms with Iithium in Iiquid cadmium have been completed, as well as the demonstration of the use of centrifugal pumps for the transfer of salt and cadmium between process vessels Argonne researchers are currently investigating the use of pumped filtration units for the removal of insoluble such as UO_2 (uranium oxide) from the process, the filters will then be sent to the metal waste stream (16)

[1] For example the Iodine Isotope I- 129 IS a toxic radioactive fission product whereas another isotope I -127 IS a naturally occurring nonradioactive form of iodine As an analog of the more toxic I-129, 1-127 has physical properties that are very similar to I- 129 and can be used more safely to test chemical process development

methods. Although experience with actual reprocessed spent fuel is lacking, salt waste generated from recycling spent ALMR/IFR fuel by these processes can be expected to be quite different from PUREX aqueous waste and will require the development of special treatment processes (56). Argonne researchers have experimented with various salt waste forms (17). However, if current plans for developing salt waste treatment are not successful, recovery and recycling of some types of waste materials may conceivably require processes that would generate aqueous waste forms (56). Experience suggests that several kinds of water-based separation processes could be used to recover some wastes that do not lend themselves to nonaqueous treatment (56). As another option, Argonne researchers are also considering the possibility of vitrifying ALMR/IFR waste (17).

LWR Spent Fuel Reprocessing System

Argonne researchers are beginning to design equipment for reprocessing existing and future spent LWR fuel from U.S. commercial nuclear reactors to recover the actinides, including plutonium and uranium, for making new ALMR/IFR fuel. Recently, this feature has become a central goal of their research program and has been renamed the "ALMR actinide recycle system" to reflect this shift (35). The overall plan is that ALMR/IFR technology might be used to remove the plutonium, uranium, and other actinides in existing commercial reactor spent nuclear fuel by transforming them into radioactive fission products. Promoters of this idea think that this maybe a more acceptable waste form for repository disposal. In principle, over a period of centuries—with repeated reprocessing in many ALMR/IFR systems deployed around the world—much of the existing world's inventory of plutonium and other actinides in spent fuel could be transformed. Of course, in the process, quantities of plutonium would be contained in ALMR/IFR reactors or fuel reprocessing plants.

Argonne researchers hope to make the LWR process compatible with the electrorefiner designed for reprocessing spent ALMR fuel by using the same temperatures, reagents (salts), and waste forms and treatments. Plutonium and other transuranic actinides will be recovered for ALMR fuel, while uranium may be recycled for ALMR or LWR use, or disposed of (16). As with spent ALMR/IFR fuel, the reprocessing of spent LWR fuel inventories will require shielded hot cell facilities for handling the spent fuel, recovering actinide elements, and processing the resulting radioactive wastes, which will include highly radioactive fission products.

Officials at DOE and Argonne indicate that the research and development of the LWR spent fuel reprocessing system lags significantly behind that of other components of the ALMR/IFR fuel cycle system (11, 28) (figure 3-2). Others add that the use of electrorefiner technology for the conversion of spent LWR oxide fuel into new metal fuel may be very difficult. "The fact that LWR fuel is oxide and the [Argonne] conceptual process is a nonaqueous process requiring conversion of all of the oxide fuel material to metal poses process development problems that may not be easily solved" (56). According to Argonne researchers the process chemistry has been selected. The next step would be the design of a prototype system. During 1993, an experiment was conducted by Argonne using materials that resemble LWR fuel (without fission products), and a small quantity (20 kilograms) was transformed from the oxide to the metal (16). According to current plans, building a prototype of this system for demonstration purposes with actual irradiated fuel may be completed by FY 1997 (see figure 3-2).

Uranium is the most abundant material in LWR spent fuel. If it is to be eliminated by this process (i.e., completely converted to fission products), it would first have to be transmuted into plutonium, then reprocessed into new fuel, and finally fissioned in the nuclear reactor. This would require breeder operation and the production of plutonium over many decades before actinide elimination might be completed. It would also result in the wide deployment of ALMR/IFR nuclear reactor systems that would both require additional plutonium for continued operation, if for example they were to continue to generate electricity, and be capable of breeding more plutonium. Thus, the net effect may not be to decrease the world plutonium inventory, because plutonium would be contained in recycled nuclear fuel in ALMR/IFR systems spread around the world. These systems would also provide facilities and equipment that could be modified for small-scale plutonium purification, described later. Thus, from a long-term standpoint it is not clear whether large-scale ALMR deployment would be preferable to a plan that would place existing spent fuel in geologic repositories, should they become available (30).

Waste Management Issues

The potential impact of actinide removal on the long-term management of spent nuclear fuel has been the subject of a number of analyses. Some argue that the difficulty of developing geologic repositories cannot be **reduced** by merely making technical modifications to the waste because issues of siting, fairness, scientific uncertainty, and public trust override technical barriers (18). In any event, use of the AL MR/IFR technology for "actinide recycling'* of LWR spent fuel would in effect transform actinides into highly radioactive fission products that would have to be treated and disposed of in some suitable repository.

Argonne researchers expect that the most problematic waste fission products, such as iodine and cesium isotopes (because of their very long half-lives and water leaching potential), would be encapsulated in a mineralized form similar to a vitrified glass log for disposal in a geologic repository. Other fission products including technetium, strontium, zirconium, and carbon isotopes might be encapsulated in a metal ingot form. The researchers hope that these waste forms might prove to have equal or even greater groundwater-leaching resistance than the original LWR fuel rods (17, 28). It has been difficult for repository designers to prove the engineering reliability of safe spent fuel storage over man y centuries, and it is not clear that the new waste forms proposed by Argonne researchers will be any easier to evaluate.

Argonne researchers also think that by removing actinides from the LWR spent fuel, the wastes will be made more readily acceptable to the U.S. public for repository disposal. In part this is because the greatest amount of long-term radioact ivity is due to the actinides in the spent fuel, although some fission products are also long-lived. Others conclude that the impact on public acceptance will be minimal because although actinides contribute the majority of the total long-term radioactivity in spent fuel, they are much less water soluble than the fission products. Thus long-term *leakage* risks from a geologic repository come more from long-l ived, water-soluble fission products such as technetium-99 (half-life 210,000 years) and iodine- 129 (half-life 17 million years) than from actinides (5, 19, 46).

DOE officials are also quick to point out that they consider all such exposure risks from repositories, including leakage, to be extremely low (46). Some environmentalists argue that a lower environmental impact would result if all materials contained in spent fuel remained in the spent fuel rods they are presently in, and that any reprocessing will inevitably increase the risks of environmental releases due to increased handling and transportation during reprocessing (28).

Evaluation of the ALMR/IFR Technology 4

The advanced liquid metal reactor/integral fast reactor (ALMR/IFR) project within the Department of Energy (DOE) is currently a research project, and the key components necessary for proposed future applications which are reviewed in this chapter, require considerable development and testing. As described in chapter 3, many of these key components are still under development, at the concept stage, or still being tested. For example, studies are just beginning on the behavior of reprocessed ALMR/IFR nuclear fuel over its lifetime and may require as long as 5 years for completion.[1] In addition, the existing experimental breeder reactor (EBR-II), which is part of the test complex, is now scheduled to be shut down at the end of 1994. Fuel behavior studies are needed for each of the variety of fuel types proposed for the ALMR/IFR system, including those based on reprocessed spent light-water reactor (LWR) fuel, recycled ALMR/IFR fuel, and surplus weapons-grade plutonium. It is not clear how these studies will proceed without the EBR-II.

Many components of the ALMR/IFR fuel reprocessing and recycling system have been demonstrated on a bench scale. However, most have yet to be tested as prototypes or at a full production scale, or to be integrated into a complete operating system. In addition, the waste disposal technology for the system is still in an early research stage. Only after such research, development, and prototype work is complete could a commercial-scale ALMR/IFR system be deployed. Because of the nature of any research project in which both problems and opportunities have yet to be

[1] Unrecycled or reprocessed experimental fuels have been tested in the nuclear reactor for some years.

discovered, it is difficult to evaluate the suitability and potential of the proposed system for any specific goal. Such a research project will change and adapt in response to data gathered during its development. Thus, the Office of Technology Assessment (OTA) analysis therefore reflects that uncertainty. It also reflects the fact that all recent technical data available on this project have been developed by DOE contractors-Argonne National Laboratory and the General Electric Company (GE).

DISPOSING OF WEAPONS PLUTONIUM

ALMR/IFR technology has been proposed as an option for eliminating surplus military plutonium in both the United States and the former Soviet Union by converting and using it as nuclear fuel. Theoretically, with enough multiple fuel reprocessing cycles through an ALMR/IFR system, virtually all plutonium isotopes in the original weapons material and in reprocessed fuel could be converted into fission products. However, as discussed in chapter 3 and supported by previous studies, this technology would take more than a decade of research to build, require several hundred million dollars in research expenditures, and face uncertain outcomes (27, 37, 46, 48). To speed up the process, promoters of the technology have proposed that the surplus plutonium could initially be "deweaponized” by blending it with fission products (to make it too radioactive to handle outside a hot cell) and later returned to an ALMR (when one is developed) for complete fissioning (53). Such an approach may be feasible, but it is not unique to ALMR technology.

A consideration pointed out by the National Academy of Sciences (NAS) and others is that it may be inappropriate to wait for the possible development of the ALMR/IFR system before dealing with the problem of Russian plutonium now coming from warhead dismantlement. Many experts agree that the existence and status of that plutonium represent a “clear and present danger,” and that advanced reactor concepts such as the ALMR/IFR are too far from realization to be considered useful disposition options for this material (27, 48). Given the status of development of the ALMR/IFR system, it will not be operational for decades. If current plans and budgets are followed, a prototype system scheduled by Argonne and GE researchers could begin operation about 2005. When the time necessary for technical, environmental, safety, and siting evaluations is considered, substantial ALMR/IFR capacity is unlikely to be available until about 2015 at the earliest.

If disposition of plutonium is urgent, other more immediately available and technically mature options, such as conversion into mixed-oxide (MOX) fuel and burning in existing nuclear reactors or vitrification, should be viewed as near-term preferred choices. Even if it were completed and performed as specified, the ALMR/IFR system requires substantial time for the elimination of large amounts of plutonium. In a maximized burner configuration (operating to burn the most plutonium possible), a full-sized commercial-scale 1 -gigawatt ALMR/IFR installation could destroy (by fissioning) only about 0.4 metric ton of plutonium per year (42, 45).

The use of ALMR technology for the complete destruction of surplus weapons plutonium would probably not be feasible as a stand-alone mission for this technology. It would have to be coupled with some other plutonium fuel source in addition to surplus weapons plutonium (e.g., material recovered from LWR spent fuel), because a minimum amount of plutonium must always be present in the ALMR for the reactor to function. For example, a hypothetical full-scale ALMR would require an initial plutonium fuel load on the order of 15 tons to begin operation. In the burner mode, after a fuel load was used up in approximately 2 years, it would be removed, and the remaining plutonium would be recovered during reprocessing to make new ALMR fuel. Only about 0.4 tons of new plutonium would have to be added per year to make up the reactor core load.

In other words, about 15 tons of weapons plutonium would be needed to initially load the reactor, but only about 0.4 tons would be transformed to fission products each year, and this would have to be replaced for continued reactor operation. When no more weapons plutonium was available as makeup fuel, slightly less than 15 tons of plutonium would remain in the reactor core. Thus, if the above-mentioned 1 -gigawatt reactor operated to consume plutonium for as many as 50 years it could destroy about 20 tons of plutonium, but would require about 35 tons to operate, leaving about 15 tons of plutonium in the system at the end of the 50 years. Under these conditions, only about 60 percent of the 35 tons of plutonium required for reactor operation would be destroyed. Further reactor operation to fission the remaining 15 tons would require a new source of plutonium other than dismantled weapons.

Another issue related to estimating the time to deployment is licensing and siting. If the ALMR were licensed in the manner of other civilian nuclear facilities, the process must be expected to require several years. Argonne and GE expect that licensing by the Nuclear Regulatory Commission (NRC) would be possible, and they have submitted a preapplication review to NRC that is now complete (44). The NRC review concluded that the concept is licensable, specifically including seismic isolation, fuel integrity, and emergency shutdown aspects (12, 44). This was a preapplication review, and further licensing could be subject to future questions and debate. If the ALMR were deployed by the private sector, licensing could elicit public concerns about plutonium reactors in general. An alternative licensing process would be to carry out operations at government sites in Russia and the United States to avoid the debate about proliferation issues that the use of multiple ALMR/IFRs would entail (53). Some believe that a very lengthy public debate about licensing and siting can be avoided if the only intention is to license several reactors at government sites operating with surplus weapons plutonium (27).

Plutonium storage could also bean issue if a decision is made to wait until the ALMR/IFR technology is developed before surplus weapons plutonium is processed. In that case, today's surplus plutonium may have to be stored for decades while ALMR technology is designed, tested, scaled up, deployed, and licensed. Some believe that the use of breeder reactors such as the ALMW IFR will make economic sense as a means of meeting future U.S. energy needs, and therefore the United States should store its military plutonium for this eventuality. Others point out that plutonium-fueled fast breeder reactors will not be economically competitive with current reactors for probably a century (37, 46). Plutonium could become an economic energy source only if uranium becomes much more expensive or the world's uranium resources become scarce. Most experts agree that, at present, the cost of fabricating and safeguarding plutonium fuels makes it uncompetitive with cheap and widely available low-enriched uranium fuels (27).

In a recent report, the National Academy of Sciences concludes that advanced reactor designs will not be available for plutonium disposition for many decades, and thus it makes little economic sense to store existing plutonium against this eventuality, especially when there are much more near-term disposition methods available (27). NAS also concludes that current decisions about disposition options for surplus weapons plutonium should not be used to drive decisions about future options for nuclear power in the United States. The amount of weapons plutonium likely to be surplus is small on the scale of global nuclear power use and is not a large factor in the future of civilian nuclear power (27). Another issue is that whatever economic value plutonium might have in the future must be considered in light of the security risks it may present. There is also a danger that long-term storage of military weapons plutonium awaiting a disposition technology may send the wrong political signal to the rest of the world about U.S. plutonium management goals.

Finally, the selection of any disposition option must await formulation of an overall national policy for managing plutonium and other nuclear materials from dismantled weapons that states the key, relevant criteria (48). Meanwhile, certain features of the ALMR/IFR concept-its potential capacity to protect plutonium from proliferation and its development status-can be used by policy-makers to compare and evaluate it against other plutonium management options. A careful assess-

TABLE 4-1: Half-Lives of Some Fission Products and Actinides Contained in LWR Spent Fuel

Spent fuel nuclide	Half-life (years)
Technetium-99 (fission product)	210,000
Iodine-129 (fission product)	17,200,000
Cesium-135 (fission product)	2,000,000
Uranium-234 (actinide)	248,000
Plutonium-239 (actinide)	24,360
Americium-241 (actinide)	458

SOURCE *Handbook o/ Chemistry* and Physics, 48th Ed (Cleveland, OH The Chemical Rubber Company, 1967)

ment, independent of all reactor vendors and proponents of certain technologies, would be beneficial. Such an assessment might consider which criteria are most important in both the United States and the former Soviet Union, and evaluate the technology options against those criteria. Recent studies cited above could be used as a starting point for such an assessment.

NUCLEAR WASTE MANAGEMENT

Waste volume and characteristics are important factors in assessing potential applications of the ALMR/IFR concept. Because this concept is still in research and development stages, and has not been tested with actual spent ALMR/IFR fuel, its potential impact on waste reduction must be projected from available data. Nevertheless, developers of the ALMR/IFR cite some anticipated advantages of the system based on its minimization of waste.

I Processing Spent Reactor Fuel

Developers of the ALMR/IFR claim it may be possible to remove (by repeated reprocessing over time) the actinides from LWR spent fuel, including plutonium and uranium, leaving only the generally shorter-lived (but initially very radioactive) fission products, which would then be packaged for geologic repository disposal. However, the potential impact of ALMR processing on geologic repositories for spent nuclear fuel is far from clear. ALMR researchers claim that the removal of actinides from spent fuel (for recycling into ALMR fuel) would reduce the duration of radiological toxicity of such waste from millions of years to hundreds of years because a large portion of the long-lived radioactive isotopes would be removed (12).

Others have disputed some of these claims, based on calculations of the impact of actinide removal on key geologic repository parameters. Also, its developers claim that the ALMR/IFR might be able to eliminate a variety of problematic nuclear wastes, converting the actinides they contain into fission products. Others counter that actinide removal would offer few if any significant advantages for disposal in a geologic repository because some of the *fission product* nuclides of greatest concern in scenarios such as groundwater leaching actually have longer half-lives than the radioactive actinides. The concern about a waste cannot end after hundreds of years even if all the actinides are removed when the remaining waste contains radioactive fission products such as technetium-99, iodine-1 29, and cesium-135 with the half-lives between 213,000 and 15.7 million years (table 4-1) (5, 18, 19).

A final advantage of actinides removal (including plutonium) from spent fuel is to eliminate concerns about leaving plutonium in a repository that might be mined sometime in the future for the purpose of making weapons. This is a legitimate point that should be considered more broadly in the context of future proliferation potential.

In the proposed operation of the ALMR/IFR actinide recycle concept, the actinides separated from spent fuel would be converted into new fission products, that require disposal. Thus, this system does not eliminate the need for a nuclear waste repository, nor can it be considered a short-term solution to the U.S. spent fuel disposal problem. Also, unless the deployed ALMR/IFRs were permanently shut down and decommissioned at the end of this mission, they might continue to be used as breeder reactors for electricity production. In that case they would continue to produce radioactive fission products that would require disposal. Numerous other technical ques ions relating to proposals to eliminate plutonium n spent fuel by using various technologies are currently being evaluated by the National Academy of Sciences Panel on Separations Technology and Transmutation Systems (STATS panel).[2]

Processing all U.S. spent reactor fuel to remove actinides is likely to be very slow and require decades to significantly reduce the actinide content of existing LWR spent fuel (26, 27, 46). With a national deployment schedule. ALMR/IFR technology might permanently destroy a significant portion of U.S. spent fuel after 60 to 90 years (3). Another estimate is that it would take 20 ALMR/IFR facilities 100 years or more to destroy 90 percent of the LWR actinide waste inventory projected to exist in 2010 (26,). Each reprocessing cycle of LWR spent fuel in the ALMR/IFR system would transform and remove only a small proportion of the total actinides originally contained in LWR spent fuel, so that a great number of reprocessing steps would be required to transform all of the actinides. LWR spent fuel contains only about 1 percent plutonium, with the remainder being mostly uranium, much smaller amounts of other actinides, and fission products. Separating the plutonium would leave the vast majority of the LWR spent fuel material, mostly uranium-238, which would still require disposition. One proposal is to convert this surplus uranium-238 by breeding it into new plutonium fuel in the ALMR/IFR. During the course of this operation, much more plutonium would be generated than was present in the original LWR spent fuel.

In terms of the potential regulatory impact of an actinide recycling program. one study concluded that because of Environmental Protection Agency and NRC rules, acinide recycling would not make licensing of a repository significantly easier. A study on the potential of ALMR actinide recycling (and several other reprocessing/disposal technologies) for handling spent nuclear fuel concluded that the concept was flawed on both technical and poitical grounds. and that ALMR actinide recycling was neither an alternative to the current geologic disposal program nor essential to its success (36). In fact, the conclusion reached was that pursuit of such a program would require a major restructuring of the U.S. geologic repository effort because the waste forms generated would be so different (36). The study pointed out that even if the efficiency of spent fuel actinide recovery claimed by proponents were feasible on an industrial scale. it would solve the wrong problem. Many of the risks of a long-term geologic repository come not from the actinides contained in spent fuel but rather from long-lived soluble fission products that might leach from a repository into groundwater, which would not be eliminated by the ALMR/IFR system. In addition. the absolute radioactivity risk from a repository is already very low, and actinides do not contribute significantly to that risk.

Further, some argue that actinide recycling would aggravate rather than reduce public concerns by requiring the siting and operation of numerous reactors, as well as reprocessing and fuel fabrication facilities; by reviving the concerns over nuclear proliferation; by generating new and different waste streams: and by requiring centuries of reliable institutional control over power-producing, reprocessing, and storage facilities. Removing the actinides from radioactive waste is unlikely to have a significant impact on public antipathy to geologic disposal (23. 46).

It appears that actinide recycling is unlikely to reduce the difficulty of managing the overall waste stream from nuclear power reactor operations. In fact, the opposite is possible. New licensing. the operation of reprocessing facilities, transportation between the present locations of LWR spent fuel and reprocessing facilities, and management of ancillary waste streams would all be required. Finally. if the ALMR/IFR becomes a widely deployed technology for electricity generation, as envisioned by its developers, the net

[2] This report is scheduled for release in July 1994.

impact in the long term would be to *increase* the repository capacity required for the disposal of fission product wastes created by the technology.

I Processing Other Radioactive Wastes

According to Argonne researchers, the same technology that might convert LWR spent fuel into ALMR/IFR fuel would in principle be applicable to the processing of other types of nuclear waste materials. These would include DOE-owned spent fuel, surplus weapons plutonium, and scrap from plutonium processing operations (16). According to a recent DOE report, the problem of dealing with a large number of old and disintegrating fuel elements from its past operations is reaching critical proportions (52).

Since the ALMR/IFR technology will not be available soon, it may not be appropriate to consider its application for the most pressing and immediate waste disposal needs outlined by the DOE Spent Fuel Working Group. Nevertheless, some method for improved safe storage of this waste is urgently needed. And if parts of the ALMR technology could be developed for treating and packaging this material or similar waste further, investigation might be useful.

In summary, the ability of ALMR/IFR technology to reprocess LWR spent fuel into ALMR fuel has yet to be demonstrated, and significant technical problems remain, one possible application is for long-term management of radioactive wastes that do not require immediate attention. Because of the preliminary nature of research on the ALMR/IFR concept, characterizing its potential impact on a geologic repository for nuclear waste in terms of waste volume, longevity in a repository, or long-term risk factors, is difficult. Thus, it is also difficult to make comparisons with much more developed processes, such as direct disposal of spent fuel in geologic repositories or high-level waste vitrification.[3] Furthermore, any spent fuel reprocessing option must be evaluated in the larger context of establishing a U.S. plutonium reprocessing policy or of reviewing international policies regarding nonproliferation.

PROLIFERATION RISKS AND BENEFITS

I Concerns About Plutonium Breeding

Although some recent proposals for the future of the ALMR/IFR concept have focused more on its ability to transform and irreversibly use up plutonium, even its developers acknowledge that it is "uncontested that the IFR can be configured as a net producer of plutonium" (13). In principle, any nuclear reactor could be operated as a breeder (producing new plutonium). However, as mentioned earlier, the ALMR/IFR system originated as a reactor capable of reprocessing its own spent fuel and breeding more plutonium (42). In fact, liquid metal reactor (LMR) technology has always been associated with breeder reprocessing technology. The first reactor ever to produce electricity, which began operation in 1951, was a liquid metal cooled-breeder reactor design. In September 1993, ALMR/IFR developers emphasized the possible long-term energy advantages of the concept as a breeder reactor design (4). GE representatives described the flexibility of converting their full-scale reactor design from burner to breeder operation in a November 1993 status report to DOE (21, 34).

Thus, for the purpose of evaluating the potential impact of the ALMR/IFR on nuclear proliferation risks, it must be considered a breeder-capable reactor system. Even though this system might be capable of operating in a way that uses up plutonium from sources such as dismantled weapons, if properly modified it could also be used to breed more plutonium. Most proponents of the technology believe that its long-term mission will probably always be as part of an integrated system in which plutonium fuel and reprocessing make significant contribution to U.S. and world energy needs.

[3] Although vitrification is still under development in the United States, it has been demonstrated successfully in France and the former Soviet Union as a means of solidifying high-level radioactive waste. No vitrified waste has been placed in a repository, however.

If reactor design allowed sufficient room, a "breeder blanket" of fertile uranium-238 could be retrofitted around the reactor core that, when irradiated, could produce plutonium with a relatively low buildup of undesirable (from a weapons manufacturing standpoint) plutonium isotopes.[4] Breeder blankets have also been used to produce weapons-grtidc plutonium in LWRs. Some argue that the ALMR could be designed to allow no room for such a blanket of breeding material around the retie' t o r core. I n this case, however, although less efficient it would still be possible to breed plutonium by placing fertile material at either end of the fuel rods.

However, the designs recent] y described by GE do not require any extra room in the reactor core. They are designed to be flexibly convertible from breeding to consuming by simply altering the arrangement of a fixed number of reactor elements (for example, see figure 3-3). Thus, operatirrg an ALMR/IFR system to breed plutonium would probab]y not be difficult. It would, however, be difficult to design an ALMR reactor core that could not be converted to breeder operation given sufficient motivation and ability on the part of the reactor's owner. Any reactor could theoretically be converted to breeder operation. so the important proliferation concerns may be the access to a heavily shielded hot cell and fuel reprocessing equipment. along with access to a spent fuel source (e.g, the ALMR/IFR).

Although acknowledging that the ALMR/IFR is a breeder reactor system. its developers nevertheless claim that it has distinct proliferation advantages compared with curlier breeder/reprocessing systems such as the Clinch River Breeder Demonstration project that ended in 1983. The major difference between the two programs is the substitution of pyroprocessing for PUREX nuclear fuel reprocessing. The promoters of this concept believe that a switch to pyroprocessing by nations currently using PUREX reprocessing, including Japan, France, England. and North Korea, would represent a major step in nonproliferation. Others point out that it is difficult to justify the U.S. funding development of possible PUREX reprocessing substitutes for nations that clearly have not agreed to adopt them should they ever become available (27).

I Concerns About Weapons-Usable Plutonium

How does pyroprocessing differ from PUREX reprocessing in terms of inherent nuclear proliferation risks? One of the larger proliferation barriers claimed for ALMR/IFR reprocessed fuel is the presence of residual fission products and actinides that are highly radioactive. The irradiated fuel from an ALMR/IFR recycling facility could consist of up to 70 percent plutonium and 30 percent uranium and other actinides, along with small amounts of highly radioactive fission products. This radioactivity would make the material difficult to work with and require that all operations be carried out by using a heavily shielded remotely operated hot cell. Presumably it would be difficult to fabricate weapons components under such conditions with this material. Plutonium from PUREX reprocessing does not contain these fission products and thus can be used directly to fabricate weapons components. On the other hand, fuel from the ALMR/IFR cycle would be a preferable starting material for converting to weapons material compared with ordinary spent nuclear fuel from a conventional LWR because it contains a much higher concentration of plutonium (70 percent versus 1 percent) and significantly lower quantities of radioactive fission products. A large fraction (but not all) of the fission products would be removed by the pyroprocess. Thus, to obtain enough plutonium for a bomb it would be much

[4]Plutonium that is high in the plutonium-239 and lower in plutonium-240 and plutonium-241 is preferable for use in nuclear weapons, because the greater radioactivity and neutron generation in the latter two isotopes complicate the design of such weapons. Nevertheless, even plutonium that is high in the 240 and 241 isotopes can be used to make a nuclear bomb.

easier to handle and process some tens of pounds of reprocessed ALMR fuel than almost a ton of spent LWR fuel.

The developers of this technology point to several factors as obstacles to the use of ALMR/IFR reprocessed material for fabricating weapons. These are the reduction of the plutonium concentration by the presence of uranium and other compounds, the presence of plutonium isotopes other than plutonium-239, and the high radioactivity of contaminating compounds that makes handling more difficult. None of these, however, is a particularly impenetrable proliferation barrier. Reducing the plutonium concentration, (e.g., because of the presence of 30 percent uranium in the reprocessed material) does not itself make the plutonium unusable in terms of weapons. For example, diluting plutonium-239 with 50 percent nonfissile uranium-238 would increase the amount of material required to make a weapon by only about a factor of four (40).

The isotopic composition of reprocessed ALMR/IFR is also not an insurmountable barrier to proliferation. Plutonium is produced by the same process in both military plutonium production reactors and civilian nuclear power reactors. However, military reactors were operated differently to produce a plutonium containing mostly the single plutonium-239 isotope, which is considered the most desirable isotope for bomb production. Nevertheless, plutonium obtained from *any spent nuclear fuel source* can be used to make a nuclear bomb; therefore, no distinction should be made between weapons and civilian reactor-grade plutonium from the standpoint of nuclear proliferation (27, 37, 40).

The plutonium from ALMR recycled fuel would have an isotopic composition similar to that obtained from other spent nuclear fuel sources. Whereas this might make it less than ideal for weapons production, it would still be adequate for unsophisticated nuclear bomb designs. In fact, the U.S. government detonated a nuclear device in 1962 using low-grade plutonium typical of that produced by civilian powerplants (10, 37). The bomb design used in the 1945 Trinity test could in principle contain civilian reactor-grade plutonium of any degree of burnup and isotope composition, and still provide nuclear yields in the multikiloton range (22). Using civilian power reactor-grade plutonium in the 1945 design would increase the probability that the yield would be reduced. However, it would not greatly change the value of the "fizzle" (lowest expected) yield, which although smaller than the nominal yield would nevertheless create quite damaging nuclear explosion (22, 40). Thus, although civilian power reactor-grade plutonium would be harder to work with for making bombs, the drawbacks are not serious and nuclear proliferators might not be deterred simply because the only accessible bomb material was less than perfect.

The plutonium recovered from spent ALMR fuel would also be contaminated by heat-generating plutonium-238, but this too would not present an insurmountable proliferation barrier.[5] In any case, the plutonium recovered from the ALMR by operating it as a breeder would be relatively free of plutonium-238.

On the other hand, some processing would probably be required to remove these residual fission products from ALMR/IFR reprocessed nuclear fuel. Currently available methods for removing the residual fission products in ALMR/IFR spent fuel could be performed in the hot cell (although they might interrupt normal operation and be detectable with any inspection regime); these

[5] The details of how heat output from plutonium used in warheads would affect its design and operation are not available publicly. The NAS report concluded that the heat generated by plutonium-238 and plutonium-240 would require careful management for weapons design, including the use of channels to conduct it from the plutonium through the surrounding explosive, or delaying assembly of the device until a few minutes before use (27). Similarly, [he radiation from americium-241 in ALMR/IFR reprocessed fuel would require that more shielding be used but is not an insurmountable obstacle (27). Only plutonium composed of more than 80 percent plutonium-238 is exempted from International Atomic Energy Agency safeguards; any other isotope composition must be considered usable for making a bomb (37).

would provide usable, if not optimal material. for weapons purposes. Thus, access to the hot cell associated with ALMR/IFR technology, and with its ability to handle highly radioactive materials safely (which is not a feature of conventional LWR systems), may be a key proliferation issue. Proponents claim that the purification of ALMR/IFR reprocessed material would require either construction of or access to a PUREX reprocessing facility. others point out that there are significantly simpler methods for removing fission products, such as a commonly used industrial process known as aqueous *ion exchange* (6, 56). Los Alamos National Laboratory has routinely used aqueous ion exchange to separate radioactive fission products from plutonium. The equipment and materials used in this process are commonly available for other types of industrial separation and purification (49). Such an operation would require the type of heavy shielding offered by the hot cell of an ALMR/IFR system. [6]

Other processes available *within* the ALMR/IFR system might also be modified to produce material suitable for making a nuclear weapon. ALMR/IFR designers expect to be able to remove the fission product wastes that would accumulate in the molten salt bath of an operating electrorefiner by using zeolite ion exchange, with the molten salt as a solvent. Analogous aqueous ion exchange processes have been used routinely to separate plutonium from other actinides and fission products, Since the same physical processes would be involved in molten salt-zeolite ion exchange, given sufficient motivation, one might be able to modify the process in order to remove fission products, and generate a material that could be converted into bomb components, with only a glove box for shielding. Similarly, although the conditions are substantially different, pyroprocessing (electrorefining)-type procedures have been developed by Lawrence Livermore National Laboratory for separating the actinide americium from recycled weapons plutonium (1). However, while the ALMR/IFR process and equipment might be modified to achieve such a separation with recycled fuel, any such modifications would probably be very difficult to conceal from a credible outside inspection regime.

Thus, in providing both the necessary starting material (ALMR/IFR recycled fuel) and the necessary facilities (hot cell and related reprocessing equipment), the ALMR/IFR system could be considered a source of weapons-usable nuclear material. Whereas it would probably be easier to generate weapons plutonium from a PUREX facility if one were available, but for a determined and capable proliferator, access to an ALMR/IFR facility is likely to serve such purposes.

An independent assessment of the proliferation potential and international implications of the integral fast breeder reactor, prepared by Martin Marietta for DOE and the Department of State in 1992 (the Wymer report), concluded that the diversion and further purification of plutonium by using the facilities available in the ALMR/IFR processing and recycle facility would be possible (56). The report also noted that the modifications required for these scenarios would be readily detectable with any reasonable inspection regime and that therefore proliferation scenarios involving *treaty* abrogation were the greater concern. In other words, any diversion of nuclear materials from the ALMR/IFR would be difficult to carry out clandestinely if an inspection regime were in place (24).

The Wymer report outlined several possible proliferation scenarios in which ALMR/IFR equipment could be modified to produce weapons material, including the following (56):

- The normal recycled ALNR/IFR fuel product could be reprocessed through multiple elcctro-

[6] If the hot cell were diverted for use with aqueous plutonium purification methods such as ion exchange or PUREX, either the process would have to be operated so as not to introduce water into the hot cell atmosphere, or the normal IFR fuel reprocessing, which is highly sensitive to water, would have to be interrupted.

refiner cycles to remove the rare earth fission products and reduce the radioativity of the material, thereby making it easier to manipulate.

- Multiple batches of fuel might be processed by using only the iron cathode electrode to remove uranium and allow the plutonium to accumulate in the molten salt phase (see figure *3-4).* This could generate a material with a plutonium-to-uranium ratio as high as nine, after electrochemical transport to the liquid cadmium cathode, although other actinides and rare earths would also be present.

- The reactor could be run in the breeder configuration with reprocessing of the irradiated fertile (breeding) material. For a more preferable grade (containing a higher proportion of the plutonium-239 isotope) of plutonium, it would be desirable to schedule blanket assemblies for reprocessing when the electrorefiner salt had just been replaced and was free of contaminants. Such plutonium would still be contaminated with fission products but, under certain conditions. could deposit a material having a plutonium-to-uranium ratio of one. Multiple batches of blanket fuel might have to be processed before the better grade of plutonium could be removed from the liquid cadmium (17).

According to this analysis, the proliferation resistance of ALMR/IFR technology is more a function of the adequacy of nuclear materials safeguards than of the technology itself. If a nation possessing an ALMR/IFR system chose to abandoned safeguards (e.g., by reneging on previous safeguards agreements), the technology alone would probably offer few proliferation barriers.

The Wymer study also considered the question: If it was willing to renounce international inspection, would a nation that had access to an ALMR/IFR system have an advantage in proliferation. compared with a nation that did not have access to such a facility’? The study determined that having an ALMR/IFR facility would clearly provide a potential proliferating: nation several advantages. including a spent fuel receiving area and facilities for preparing the fuel for dissolution (56). Having an ALMR/IFR facility would be much more valuable to a potential proliferator that had no other existing reprocessing facilities. A nation that abandoned nonproliferation regimes and had existing PUREX facilities might see less proliferation advantage in having an ALMR/IFR facility.

If, instead of processing spent fuel, the ALMR system were used to reprocess *irradiated fertile (breeding) material* in the electrorefiner, the resulting plutonium would be a superior material, with an nearly ideal isotope composition for nuclear weapons manufacture (56). It would be superior even to plutonium obtained by PUREX reprocessing of conventional LWR spent fuel because of its higher plutonium-239 content. When it operates as a breeder, the plutonium available from the ALMR/IFR under normal operation will be weapons grade, whereas commercial LWRS always produce a much lower-grade plutonium unless they are shut down and refueled much more frequently than required for economical operation (49).

Developers of the ALMR/IFR technology indicate that it is an "uncontested fact that it would be technically possible to make nuclear explosives from material extracted in some (unspecified) fashion from an IFR process stream” (13). Other reports have come to similar conclusions. Even though the ALMR reduces certain proliferation risks when operated with proper safeguards, possess ion of such a facilitywould bring with it some of the technology needed to produce weapons plutonium as well (27).

ROLE OF NUCLEAR SAFEGUARDS

Part of the ALMR/IFR research program is a project to develop suitable nuclear material safeguards and monitoring and control systems. One study suggests that ALMR/IFR fuel recycling would have some features that require the development of unique safeguards and inspection systems (56). Others feel that the notion that plutonium in non-nuclear weapons countries can be made safe by the use of safeguards is misleading. That is, full-scale reprocessing and breeder development would involve such a large amount of separated plutonium that foolproof protection aga instns[version would be difficult or impossible (37).

According to the Wymer report, a safeguards regime for the ALMR/IFR system would have to be very different from that for a PUREX facility. (In fact, even safeguards for large-scale PUREX-type reprocessing plants remain to be proven in actual operation.) Conventional safeguards systems for PUREX rely heavily on materials control and accounting techniques in which representative samples of key, homogeneous solutions are taken during plant operation. Chemical analyses of these samples give an accurate and precise picture of the movement of materials through the PUREX reprocessing system. Such an approach may be less applicable to the ALMR/IFR system because of the lack of homogeneity of molten salt solutions used in pyroprocessing and at other key points during operation. In the clectrorefining process. for example, plutonium (along with other actinides) may actually precipitate from solution. leading to misleadingly low measurements (24). Safeguarding the ALMR/IFR system would therefore have to rely more on containment and surveillance methods. Similar methods have been developed as proliferation control techniques at sites such us Sandia National Laboratories (24). The development of adequate safeguards for the ALMR/IFR system may be an essential requirement to allow its future development and deployment (24). However, International Atomic Energy Agency (IAEA) inspection would always require actual hands-on monitoring of a facility.

According to one analysis, if nonnuclear countries obtain full-scale reprocessing plants and breeder reactors, even full safeguards may not provide timely warning if a country should decide to abrogate its safeguards agreements (37). Thus, no safeguards scheme. including any IAEA program, could be effective if such sensitive materials and facilities became widely available in nations that are current I y nonnuclear weapons states. This is because the possession of such facilities would allow a nation to build nuclear weapons too quickly for adequate international response. A year hasbeen estimateded as the time necessary for the United States and others to amass sufficient political and other pressures to prevent a proli ferating country from making a bomb. The only acceptable approach, therefore, may be for nonnuclear countries to completely forego nuclear reprocessing. Then, if a country seized spent fuel. it would still need 1 1/2 to 2 years to build the necessary reprocessing facility to extract the plutonium—time enough in them-y for the rest of the world to take heed and respond.

Supporters suggest that a key difference between ALMR/IFR technology and PUREX plutonium separation is that. in principle, the former would keep the entire cycle (fuel reactor burning, spent fuel reprocessing, fuel fabrication, and waste processing) at a single site. If adopted. this would elminate proliferation concerns stemming from the shipment of separated plutonium and spent fuel. Thus the configuration of the complete system. rather than the technology itself. may offer a proliferation resistance advantage compared with PUREX reprocessing. In countries currently de~cloping PUREX reprocessing for plutonium fuel recycling, such as France and Japan, spent fuel is transported to central facilities and reprocessed fuel must be transported back to the reactors. On the other hand. the United States prescnt-Iy curries out no reprocessing. If the United States begins reprocessing. there may be no technical reason why reprocessing facilities including PUREX could not be colocated with a nuclear reactor, if this were determined to be an important feature. In addition, GE acknowledges that it may be politicall y difficult to colocate reprocessing facilities at new nuclear reactors, and it is considering the possibility of a central reprocessing facility that could serve many reactors at different locutions (43). Therefore the collocation advantage may be an equally infeasible option for either IFR or PUREX reprocessing.

POLITICAL BARRIERS

Separate from the issue of whether the ALMR/IFR system could provide sufficient tcchni(w[*barriers* to proliferation is the question of the program's impact on political barriers to prlifera-tion. In particular. how much might a United

States decision to reprocess and bum plutonium influence the plutonium management policies of other countries? Since the late 1970s the United States has chosen not to carry out plutonium reprocessing for both economic and political reasons. In a September 27, 1993, policy statement the Clinton Administration reaffirmed this by announcing a nonproliferation initiative, which includes a proposal for a global convention banning production of fissile material (e.g., plutonium) for weapons, a voluntary offer to put U.S. excess fissile materials under IAEA safeguards, and a recognition that plutonium disposition is an important nonproliferation problem requiring international attention (55). Subsequently, President Bill Clinton and Russian President Boris Yeltsin, during their meeting in Moscow on January 14, 1994, agreed to cooperate with each other and other states in measures designed to prevent the accumulation of excessive stocks of fissile materials and to reduce such stocks overtime (3 3). They agreed to establish a joint working group to consider steps to ensure that these materials would not be used again for nuclear weapons.

Many are concerned that a U.S. emphasis on ALMR/IFR development, with its inherent reliance on nuclear fuel reprocessing, could undermine this policy and stimulate other nations to undertake plutonium reprocessing programs. In his September 1993 statement, President Clinton said that although the United States will not interfere with reprocessing in Japan or Europe, “the United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes” (55). If the United States breaks this long-standing norm by proceeding with the development of plutonium reprocessing technologies, other nations might be encouraged to consider LWR fuel without necessarily limiting the types of technologies used.

The example set by the United States in any decision about reprocessing for commercial reactors is likely to prove an important influence on the behavior of other countries and should be carefully considered. Setting an example for other nations has long been a primary argument for not supporting U.S. breeder reactor development. The NAS and others have warned that U.S. policy on plutonium disposition must take into account the signals sent by the choice of a particular disposition method (27). For example, if the United States treated its weapons plutonium as a waste to be disposed of, this could set an important example in its desire to discourage the use of plutonium reprocessing.

In summary, any nuclear technology carries with it some proliferation risks. These risks might be minimized by using inspection and safeguards regimes. However, the effectiveness of these measures is based more on political and international norms than on purely technical barriers. If the ALMR/IFR reprocessing technology were exported, the United States could not guarantee its ability to impose and enforce enduring and reliable technical barriers on other nations.

If the proliferation resistance of ALMR/IFR technology is judged from a purely technical viewpoint, its reprocessing facilities and nuclear reactor could clearly be adapted to breeder operation for producing plutonium. In addition, the technology carries with it several issues of general proliferation concern beyond whether it is designed as a breeder or a burner of plutonium. In itself, the use of reprocessing and its collocation with hot cell facilities provide some opportunity for plutonium concentration and the acquisition of plutonium for weapons. Although the ALMR/IFR system might prove more difficult to misuse for weapons production than a PUREX facilit y, its operation would produce a much more concentrated form of plutonium compared with spent LWR fuel, and would provide a facility (hot cell) and a technology for handling and reprocessing spent fuel into a weapons-usable form. Thus, from a purely technical viewpoint, if ALMR/IFR replaced or were developed as an alternative to PUREX-based reprocessing, it might be an incremental improvement nonproliferation. If it replaced the conventional LWR reactor with a once-through fuel cycle followed by direct disposal, then it could increase the risk of proliferation.

BEYOND THE SPENT FUEL STANDARD FOR PROLIFERATION RESISTANCE

ALMR/IFR promoters have focused attention on the fact that any plutonium contained in LWR spent fuel is a legitimate nuclear weapons proliferation concern. They and many others, including the recent NAS study on plutonium disposition, point out that there are large quantities of plutonium in low concentrations tied up in spent nuclear fuel in various nations around the world.[7] Although pure plutonium from dismantled nuclear weapons in the former Soviet Union is recognized as the immediate "clear and present danger" (27), the plutonium contained in spent fuel, as well as plutonium already separated from spent fuel, also represents a significant nuclear proliferation risk (30).[8] Since the plutonium obtainable from spent fuel can be used for making a nuclear bomb, the issue of the fate of this material must be addressed by all nations. The proposal to eliminate plutonium in spent nuclear fuel by using various technologies is currently being evaluated by the so-called STATS panel of the National Academy of Sciences, discussed earlier.[9]

In the past spent nuclear fuel was considered the benchmark for proliferation resistance because of its lethal "self-protecting" radioactivity. Although it contains weapons-usable plutonium, the spent fuel from a reactor is normally so highl y radioactive due to the presence of fission products that it cannot be handled or processed by a potential proliferator without complex specitil equipment and heavy shielding such as available in the nuclear weapons complexes of the United States or former Soviet Union.

Nevertheless, over the long term, mtiny experts agree that the unseparated plutonium in spent fuel must be considered a proliferation risk (27, 37, 46). The chemistry for separating plutonium from spent fuel is described in the open literature, and the essential technologies are available on the open market (49). Although commercial-scale separation is difficult and costly, a potential proliferator could use a much simpler and less costly facility to extract enough material for a few weapons. The plutonium contained in a truckload of spent fuel rods from a typical power reactor is enough for one or more bombs (27). Moreover, the intense radioactivity that initially makes nuclear spent fuel self-protecting declines after some decades. For example, after 100 years, spent nuclear fuel of typical burnup would decay to less than 100 rads per hour at 1 meter, which is the minimum radioactivity level considered sufficiently self-protecting by the NRC and IAEA to require less safeguarding (27). The unavoidable conclusion is that any plutonium, whether military or civilian, of any form and isotopic composition could be considered a proliferation risk over the long term.

Some solutions for plutonium safeguarding (including use of the ALMR/IFR) are directed at the idea of totally *eliminating all* the world's plutonium. Promoters of this solution argue that the best action for nuclear nonproliferation would be if all nations agreed to eliminate all plutonium and plutonium manufacture. However, this would require that all nations of the world agree to dispose of plutonium in all its forms, including surplus military as well as spent fuel and civilian sepa-

[7] U.S. commercial LWRs generate about 2,000 metric tons of spent fuel each year, of which about 1 percent (20 metric tons) is plutonium and other transuranics. The current inventory of spent fuel in the United States is about 28,000 metric tons, and DOE estimates that this will grow to about 61,000 metric tons (containing about 610 metric tons of plutonium) by the year 2010 when the Yucca Mountain repository is scheduled to open. That facility has a statutory capacity limit of 70,000 metric tons of spent fuel (46).

[8] The NAS committee ranked proliferation concerns as follows:

weapons plutonium = clear and present danger; civilian separated plutonium = nearly as bad as weapons plutonium; and plutonium in spent fuel = less immediate but long-term proliferation risk.

[9] Its report is scheduled for release in July 1994.

rated plutonium (30). Some countries such as the United Kingdom, Japan, and France have made ia substantial financial commitment to the commercial use of plutonium and might not be willing to accept this (37). The NAS concluded that this option could not be available for at least the next 50 years, although it may nevertheless be worthwhile to continue its development for future needs (30).

The NAS also made the point that it would be futile to develop a plutonium disposition process that made surplus *military* plutonium more proliferation-resistant than the much larger and growing quantity of *civilian* plutonium contained in spent fuel from commercial reactors. The spent fuel standard for proliferation resistance should be considered adequate for the nonproliferation benchmark unless methods are developed that also address the plutonium contained in LWR spent fuel (27). The corollary is that if a disposition method cannot achieve the spent fuel standard for military plutonium in a few decades, with low to moderate security risks along the way, it should not be considered (30).

The NAS also warned that it is far from clear that the best long-term nonproliferation solution for all the world's plutonium is total elimination by fissioning. Some type of geologic disposal method may be superior (27). The enormous costs of eliminating the entire global inventory of plutonium cannot be justified if options such as geologic disposal can provide acceptable nonproliferation risks.[10] Some elimination options involving repeated plutonium reprocessing and reuse may even have greater proliferation risks than to disposal in geologic repositories (27). Nevertheless, the major stumbling block will be that the elimination of plutonium would require a world consensus, which is clearly lacking today. It is important that this issue not be confused with the more clear and present danger of *surplus military plutonium.* A clear distinction must be made between the issue of dealing with the plutonium supply worldwide (by elimination or repository storage) and the issue of securing weapons plutonium. However, dealing with the current *weapons* plutonium disposition issue may serve to focus attention on long-term plutonium disposition and provide new options to that objective.

Finally, any international decision to eliminate the world's plutonium supply, including that in spent fuel, must be made against the background of international policy regarding the future of nuclear energy. In other words, it might be futile to adopt policies to eliminate all plutonium if the world continues to maintain or even increase the number of nuclear power facilities that produce more plutonium (in spent fuel). In this light, the deployment of a large number of ALMR systems for the purpose of eliminating plutonium in spent fuel might actually increase the total amount of plutonium in the form of recycling ALMR/IFR fuel inventories.

[10] The NAS report concluded that any spent fuel reprocessing option would cost in the tens to hundreds of billion dollars and require decades to centuries to develop fully.

Appendix A: Abbreviations and Glossary

A

ABBREVIATIONS

ALMR	advanced 1iquid metal reactor
DOE	Department of Energy
EBR-I, EBR-II	experimental breeder reactors I and II
GAO	General Accounting Office
GE	General Electric Company
HEU	highly enriched uranium
IAEA	International Atomic Energy Agency
IFR	integral fast reactor
LMR	liquid metal reactor
LWR	light-water reactor
MOX	mixed oxide
NAS	National Academy of Sciences
NRC	Nuclear Regulatory Commission
PEIS	programmatic environmental impact statement
RFP	request for proposal
STATS	NAS Panel on Separations Technology and Transmutation Systems

GLOSSARY

Actinides

A group of the heaviest elements, beginning with actinium (atomic number 89), and including uranium and plutonium.

ALMR system

As used in this report, "ALMR system" refers to, and is interchangeable with, the integral fast reactor with its associated reprocessing, hot cell, and waste treatment facilities.

Bench scale

An experimental process (or experimental equipment), generally used in a laboratory. Bench-scale activities represent the earliest stages of developing a new process and the smallest scale of equipment that is useful in examining a process.

Breeder

A nuclear reactor designed or operated in such a manner that the net amount of plutonium remaining in the reactor core and associated components after irradiation is greater than that contained in the original fuel elements.

Burner
A nuclear reactor designed or operated in such a manner that the net amount of plutonium remaining in the reactor core and associated components after irradiation is less than that contained in the original fuel elements.

Cladding
A metal (usually stainless steel or zirconium) layer that surrounds nuclear fuel elements. This protective covering serves to contain the fuel elements and acts as a first-level container for fuel rods when stored as waste.

Electrorefiner
As used in this report, electorefiner refers to the apparatus comprised of a cathode, anode, liquid cadmium, and other components operated in a hot cell to reprocess ALMR/IFR spent fuel. It is possible that the components could be modified to allow for the reprocessing of spent LWR fuel as well.

Fission products
Atoms created when a heavier element, such as uranium, decays into lighter elements such as iodine or strontium. Some of the uranium and plutonium in nuclear reactor fuel undergoes fissioning after combining with neutrons in the reactor core, with the corresponding release of energy and more neutrons. Most fission products created in a reactor are radioactive.

Fuel cycle
A generic term used to describe the series of steps that nuclear reactor fuel systems may take, from mining and milling of uranium, through enrichment, fuel element fabrication, and irradiation. Fuel cycles are generally considered either "open" or "closed." An example of an open cycle would be conventional light-water reactors in the United States that use uranium fuel, irradiate it in a reactor, and then dispose of spent fuel as waste. A closed cycle might be a plutonium-based fuel cycle that separates and reuses the plutonium contained in the initial spent fuel for additional cycles of irradiation.

Glove box
An enclosed unit equipped with gloves through which a technician can manipulate and process radioactive materials. Glove boxes provide protection from the least penetrating form of radiation, alpha radiation, as well as prevent unintended or accidental inhalation of dust and/or particulate material. They do not offer protection against highly radioactive materials, such as spent fuel, that emit more penetrating gamma and beta radiation.

Hot cell
An enclosed structure designed to allow safe operations with the most intensely radioactive nuclear materials. Hot cells are characterized by heavy concrete or metal shielding and specially designed radiation-shielding windows. Operations of highly radioactive materials inside the hot cell are done by remote robotic manipulation. Once radioactive materials are used in a hot cell no human can enter the enclosure.

Integral fast reactor
As used in this report, integral fast reactor refers to the entire advanced liquid metal reactor system, with its associated reprocessing and waste treatment facilities. IFR is synonymous with "ALMR system."

MOX fuel
Mixed-oxide fuel, a nuclear reactor fuel consisting of a mixture of uranium and plutonium oxides.

Plutonium
A human-made element produced when uranium is irradiated in a reactor.

Prototype scale
The step in the development of a new process that follows bench scale, used to conduct tests and obtain information that may be extrapolated to full-scale deployment.

PUREX reprocessing
A water-based chemical process used to separate plutonium, uranium, and other elements and fis-

sion products, from spent reactor fuel. It was originally developed to separate plutonium for nuclear weapons.

Pyroprocessing
A nonaqueous process used to separate plutonium, and other elements, from spent nuclear fuel. Pyroprocessing is an alternative to, and distinctly different from, the PUREX process. It is a high-temperature, electrochemical procedure.

Reprocessing
A general term to describe the treatment used to separate plutonium and uranium from the fission and other byproducts contained in spent fuel. PUREX and pyroprocessing represent two different reprocessing technologies.

Spent fuel
Fuel elements that are removed from a reactor after their nuclear composition has been changed by irradiation to the extent that the fuel can no longer sustain reactor operation through fission reactions.

Transmutation
The transformation of one atom into another by any one of a variety of means-fissioning, neutron bombardment in an accelerator, and so forth.

Transuranics
Elements, including plutonium, with an atomic number higher than that of uranium (92). Virtually all transuranic elements are human-made and radioactive.

Uranium
A naturally occurring radioactive element. Natural uranium is comprised of approximately 99.3 percent uranium-238. and about 0.7 percent uranium-235, a fissionable isotope. Different "grades" of uranium exist, based on the relative content of uranium-235.

Vitrification
A waste management process that immobilizes radioactive material by encapsulating it under high temperature into a glasslike solid, sometimes with other waste forms.

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